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ORIGINAL ARTICLE

Tailing's geomorphology of the San Quintín mining site (Spain): landform catalogue, aeolian erosion and environmental implications

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Abstract
The research on tailings deposits regarding geomorphic approaches, aeolian activity and integrated physical–chemical dynamics and instability is almost inexistent. This work performs such analysis at the San Quintín Mine site, located on the Alcudia Valley region of central-south Spain. The first evidence of mining activity on San Quintín goes back to 1559 and the last one to 1988. The mine activity here produced two very different deposits. 'Old tailings' correspond to early concentration procedures between 1889 and 1923. The resulting piles look chaotic and the tailings vertically and laterally alternate with rock wastes. These deposits have been eroded, mostly, by fluvial processes. 'Modern tailings' deposits correspond to more efficient froth flotation treatments, between 1973 and 1988, when part of the old tailings were reprocessed. The grain size of these latter tailings is more homogenous, mostly sandy, which favour intense aeolian erosion. By means of a detailed inventory, we were able to identify and catalogue both fluvial and aeolian landforms, along with those produced by weathering or mass movement. We also quantified aeolian erosion, obtaining a single net wind transport rate of 12.6 t ha^{-1} $year^{-1}$, related to WSW winds. From an understanding of the geomorphic activity of the mined area, we propose guidelines for the restoration and remediation of the site, comprising wind erosion prevention measures for the modern tailings and physical stabilization through geomorphic restoration for the old tailings, combined with chemical remediation measures that have been proved useful on similar cases: open limestone channels connected to constructed wetlands.

Keywords Mining geomorphology · Tailing deposits · Aeolian erosion · Fluvial erosion · Mine restoration and remediation

Introduction

Landscapes and their associated landforms are generated and modified by a variety of processes. Erosion, sediment transport and tectonic uplift are an example of processes that have a great impact on generating natural landscapes. However, since the Industrial Revolution, a major and immediate influence on landscape does not come from those processes, but from industrial activities and human modifications of the surface (e.g. Hooke 1994, 1999, 2000; Hooke et al. 2012). Those activities can move large amounts of earth while creating new landscapes in the process. Generally, because of the fast-paced nature of these activities compared with the usual natural land forming processes, the new landforms are not stable within the local environmental conditions, often leading to accelerated erosion. Common examples of an unstable anthropic landform are the mining wastes and mine tailings, which in some cases can be huge (in the order of billions of tones of wastes from the largest mines).

The mine tailings are deposits made by the byproducts of mining activities. The volume of those deposits can vary depending on the magnitude of the mine but even small scale activities can produce tailings with considerable impact on the surrounding landscape. Because the mine tailings were usually designed to last only the mine life cycle, it is common that after that time (from a few to tens of years) the tailings start to deteriorate and in some cases, even collapse.

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This occurs specially on mine sites where the tailings are left exposed after the mine closure and, therefore, affected by adverse weather conditions. In this regard, the instability of the mine tailings implies an increasing environmental hazard, both chemical (leaching and transport of heavy metals) and physical (failure of the tailing dam and accelerated erosion) (Martín Duque et al. 2015). In fact, instability and degradation of mine tailings are currently considered one of the major sources of hazardous materials released into the environment (Sima et al. 2011). Regarding metal contamination, both surface and groundwater environments near mining sites are especially vulnerable to contamination by the release of potentially harmful elements from mine wastes deposits (Perkins et al. 2015). The release of metals to the environment occurs due to several processes, such as tailing dam failures, aeolian transport of unconsolidated tailings and chemical leaching from the tailings (Perkins et al. 2015).

Aside from metal contamination, soils and vegetation can be severely damaged by mining activities, especially opencast mining, by changing the structure of natural soils and hindering its natural function and quality (Wang et al. 2013). In addition to that, waste dumps themselves can also be considered heavily damaged land. Runoff on the mine wastes causes soil erosion, sweeping away fine materials and nutrients, impacting the possible long term development and rehabilitation of waste materials (Zhang et al. 2015).

The estimated annual global tailings generation for 2011 was approximately 7 billion tons, in addition to 56 billion tons of waste rock. In total, this is equivalent to about nine tons per human per year (Mudd and Boger 2013). That, coupled with the environmental impacts related to mine waste deposits, makes the research of effective remediation and reclamation practices a growing concern within the scientific community.

Regarding metal mine tailings, mine waste deposits and its hazard potential, most of the research and literature has previously focused on the tailings chemical composition and possible leakage of metals and metalloids to the environment. Two examples from Spain are provided by Rodríguez et al. (2009) and Oyarzun et al. (2011a, b). The former analyzed the concentration of several heavy metals in the tailings and surrounding polluted soils from a Pb–Zn mine located in the Alcudia mining district (Ciudad Real), while the second one presented an environmental study of the Mazarrón district (Murcia) focused on geochemical data from mine wastes, soils and stream sediments. Other studies have analyzed the impact of water and wind erosion on the sediment delivery to surrounding areas and their implications to the environment. Dick et al. (1995) predicted the effects of water erosion for a tailings surface using the WEPP model, while Ojelede et al. (2012) and Djebbi et al. (2017) evaluated the significance of aeolian emission and deposition from a gold mine tailings and an abandoned fluorite mine, respectively. The evaluation of erosion processes on tailings was taken a step further by Blight (1989, 2007), accounting the influence of the tailings slope length, slope angle and overall morphology of the tailings on the erosion rates.

However, very few—actually surprisingly almost inexistent—research has been carried at tailings deposits regarding both: (a) holistic geomorphic analysis, interpreting both landforms and active earth surface processes; (b) integrated physical (geomorphic) and chemical dynamics and instability. All that with the purpose of making accurate environmental impact diagnosis, prognosis and remediation/rehabilitation (if feasible and needed). Among the very few, Riley (1995) estimated the stability of a uranium mill tailings cover in Nabarlek (Australia) by a combination of modelling and analogue estimates of denudation and thresholds of rilling and gullying from areas with similar geology, topography and climate. Sawatsky and Tuttle (1996) surveyed the occurrence and growth of gullies on tailings dam walls in Northern Alberta (Canada) to ultimately assess the associated erosion rates. Following a similar perspective, Martín Duque et al. (2015) connected the landforms on abandoned mine tailings in Murcia (Spain) with the highly erosive character of the site and its impacts on the local hydrological system. Besides, from an experimental point of view, Hancock and Willgoose (2004) evaluated both through a Landscape Simulator and a Landscape Evolution Model the erosion and gully development on a mine tailings dam wall.

These four papers focus on runoff-fluvial erosion. Surprisingly, to the best of our knowledge, the scientific literature on aeolian landforms and active surface process within mined sites is inexistent. Thus, in this study, we have done a holistic inventory, classification, description and interpretation of the landforms from the tailing deposits of the San Quintín (Pb–Zn) abandoned mine site (Ciudad Real, Spain). They include weathering, runoff-fluvial, mass movement, and aeolian landforms, which can bring new insights on what are the main external processes affecting the tailings deposits. From this information, we sought to quantify the amount of materials those processes are capable of yielding to the surroundings. Once identified and evaluated the major processes involved on the geomorphic instability of tailing materials, it is easier to develop environmentally sound solutions focused on successfully tackling the aforementioned process. Here we propose some rehabilitation and remediation strategies, coupled with essential chemical stabilization and remediation practices.

All things considered, the final objective of this study is to stress the idea of the usefulness of a geomorphic approach when evaluating the conditions of decommissioned mine sites, to propose effective mine restoration and rehabilitation strategies. The elaboration of a detailed catalogue, description and interpretation of the different landforms on mining landscape, if linked to their meaning in terms of geomorphic instability, can provide basic and key knowledge about the mine tailings foreseeable future, and thus the evolution of erosion and transport of potentially contaminant wastes to the environment.

Regional setting

Physiography and climate

The San Quintín Mine site is located on the Alcudia Valley region, central Spain. The Alcudia Valley region covers a long and narrow strip of land of some $15 \times 100\ km^2$. The valley itself is surrounded by four 'sierras': Sierra Norte de Alcudia in its northern margin, and the lining constituted by Sierra Garganta, Madrona and Quintana in the southern realm (Fig. 1).

The study area is characterized by a continental Mediterranean climate, with very scarce rains in summer. Mean annual rainfall is established at around 402 mm (1981–2010 period), with strong variations between dry and wet seasons, ranging from 5 mm in August and 59 mm in December. Temperatures vary strongly throughout the year, with a noticeable annual temperature oscillation from 6 to 26.7 °C. The average annual temperature is around 15.6 °C, with maximum temperatures in July (26.7 °C) and minimum temperatures during January (6 °C) (AEMET, Spanish Meteorological Agency).

The climate also has an influence on the development of different type of soils. Overall, the most common soils on the region are classified as Entisols Xerorthent and Inceptisols Haploxerept (Gómez Miguel 2006), following the Soil Taxonomy classification system. These types of soils are characteristic of a xeric soil moisture regime, with cold and wet winters and warm and dry summers (Soil Survey Staff 2013), and represent low maturity soils with little to no development.

Geological setting and stratigraphic sequence

The Alcudia Valley region finds itself on the southern area of the Central Iberian Zone within the Iberian Massif, a geological region composed by Paleozoic materials that covers almost a third of the Iberian Peninsula. One of the most characteristic features of the region is the presence of anticlines and synclines that cross the region from WNW to ESE. These tectonic structures are generally made up of clastic sedimentary materials, locally interlayed by levels of volcanic and carbonate rocks. The whole sequence on the Alcudia Valley can be divided into three stratigraphic units comprising rocks from the Neoproterozoic to the Lower Carboniferous system (Fig. 1).

Ore deposits, mining history and wastes

The Alcudia Valley is characterized by its high concentration of ore deposits, that has historically led to a large number of small mining sites spread throughout the entire territory. Accounting for a total of 484 historical mining sites, almost 453 worked on Pb–Zn–Ag–Cu deposits, the rest being Sn–W–As, Cu, Bi and Sb deposits (Palero et al. 2003).

The San Quintín Mine group has been the major Pb producer of the Alcudia Valley Mining District. The first evidence of mining activity on San Quintín goes back to 1559. Later, during the seventeenth century, the property of the mining site swapped between various local families of nearby villages, and eventually the mines closed. However, in 1889, the "Sociedad Minera y Metalúrgica de Peñarroya" (SMMP), a French mining company acquired the property of the mining site, marking the beginning of the most successful period of Pb extraction in San Quintín, that lasted until 1912. Between 1912 and 1934 the production of Pb dramatically decreased, and a new concentration procedure was implemented with little success, leading to a new abandonment of the San Quintín Mine site.

Taking advantage of a rise in the Zn prices, the San Quintín Mine site reopened in 1973. The next 15 years, the main mining activity focused on the treatment of a three million total of derelict Zn-rich tailings produced during the last mining period (1889–1934). A flotation plant was built to treat the old tailings, and more than 95% of the head mineral produced modern tailings. To accommodate the modern tailings, a nearby stream course had to be partially diverted. Mining activity in the San Quintín Mine site definitively went to an end in 1988. During the entire mining period, the San Quintín Mine group produced more than 550,000 t of galena (PbS), 5000 t of sphalerite (Zn), and 550 t of silver. All that left behind a modified surface of 600,000 m^2, including the old and modern tailings, and rock wastes (Rodríguez et al. 2009; Martín-Crespo et al. 2015) (Fig. 2).

The characteristics of the mine wastes on the San Quintín Mine site are intrinsically related to the different mining processes and techniques used throughout the mine life cycle. Before the invention of the sulfide froth flotation process (at the beginning of the twentieth century), minerals were concentrated by gravity. One of the classic processes of separation of ore and gangue was by gravity using the so-called jigs. A jig is a simple mineral processing device that uses water and the force of gravity to separate minerals by density. Since the gangue is usually lighter than the ore minerals (e.g. galena), it is relatively simple to separate them by density. The old tailing deposits correspond in time to these early concentration procedures (1889–1923), which most certainly had many shortcomings, being the reason why these piles look chaotic and are so rich in lead. These old tailings deposit vertically and laterally alternate with

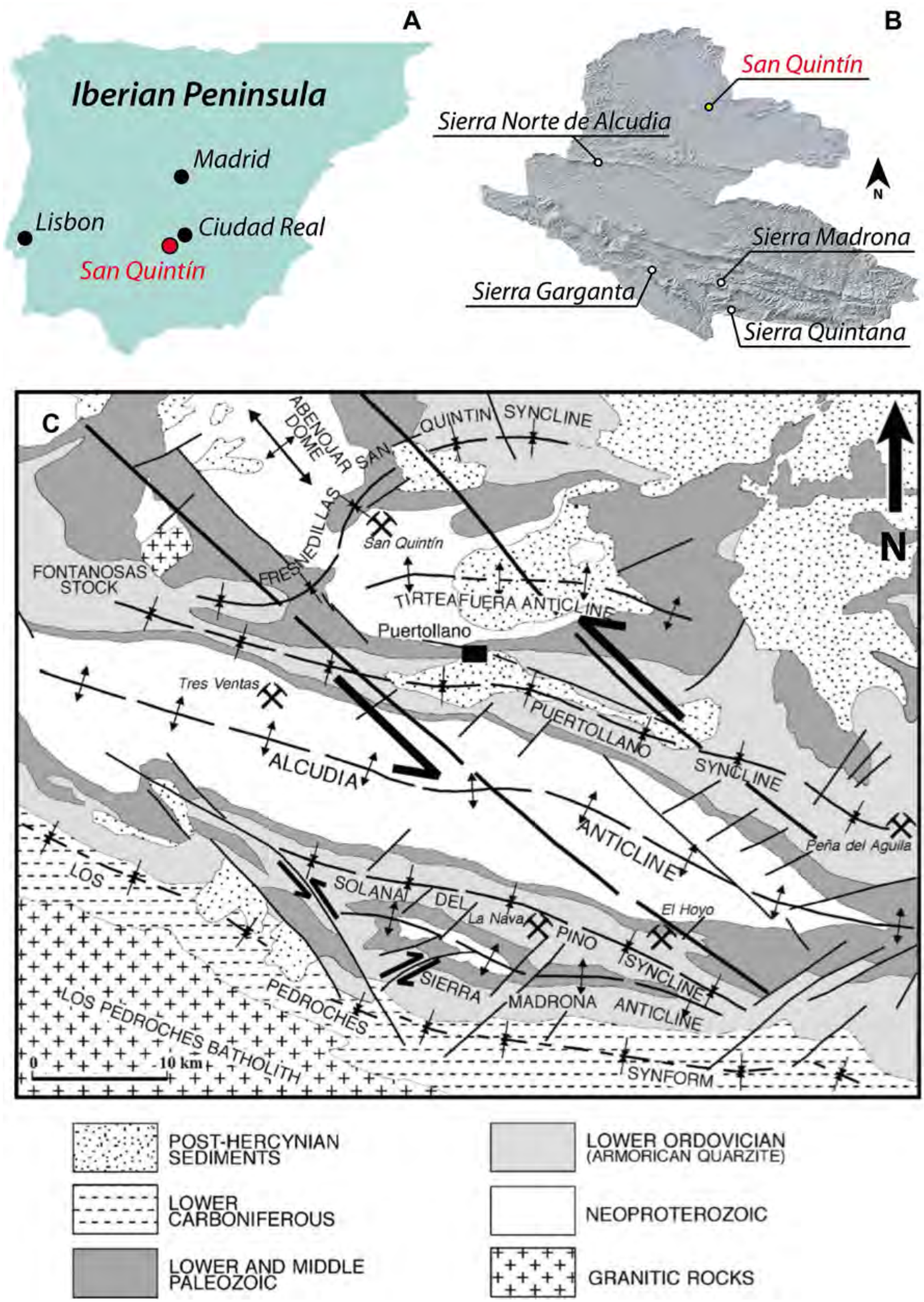


Fig. 1 **A** The San Quintín Mine site at the Iberian Peninsula. **B** The San Quintín Mine site at the Alcudia Valley Region, and its major physiographic elements. **C** Regional geology of the Alcudia Valley Region (Palero and Martín-Izard 2005), displaying the location of the San Quintín Mine site and major geological features

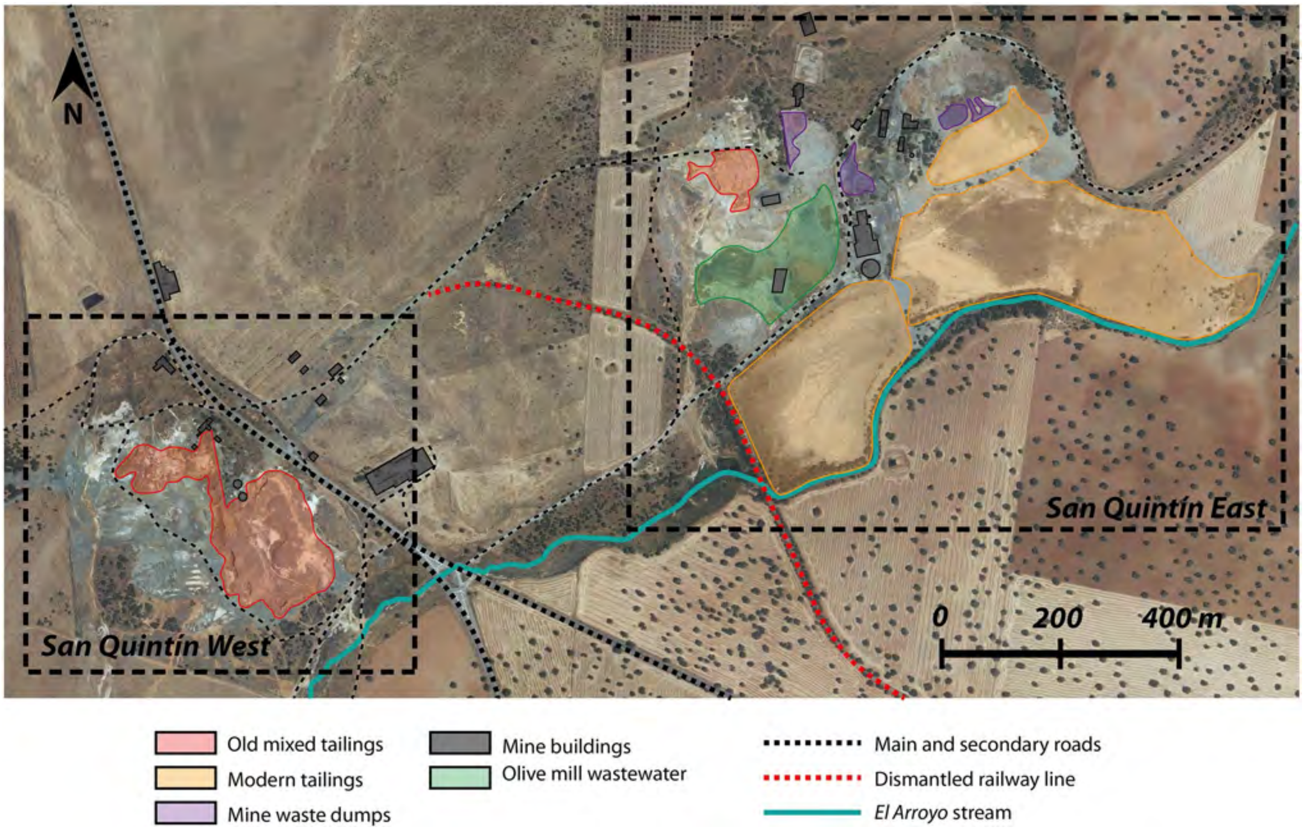


Fig. 2 Ortophoto of 2015 (PNOA 2015), representing the position and global distribution of the mine wastes and other elements of the San Quintín Mine site

rock wastes, which suggest that instead of having differentiated sites for the tailings and the rock wastes, everything was thrown in the same place (Fig. 3).

The modern and more efficient froth flotation did not reach San Quintín until the second half of the twentieth century (1973–1988), when part of the old tailings were reprocessed, this time for the recovery of sphalerite (ZnS). To this period corresponds the modern tailing deposits. There are three modern tailings impoundments. The oldest one corresponds to tailings deposited on a trough of modest size (about 9500 m^2), formed by fine-grained and homogeneous materials. The brown coloration of these tailings suggests oxidation of the residual pyrite. Of the modern tailings, one also corresponds to trough filling (about 75,000 m^2), whereas the second one is a pile of about 5 m high occupying an area of about 50,000 m^2 of extension (Fig. 3). The grain size is coarser in the latter tailings (sandy materials).

The San Quintín Mine tailings chemistry and heavy metal content have been thoroughly described in various scientific works (Palero and Martín-Izard 2005; Rodríguez et al. 2009; Oyarzun et al. 2010; Martín-Crespo et al. 2015). The tailing deposits (both modern and old) are extremely rich in Pb, Zn (in the order of thousands of μg g^{-1} of Pb and Zn), highly exceeding the reference values established for soils around the Alcudia region. This is particularly curious for the modern tailings deposits because these were generated by (supposed to be) modern procedures.

Depending on the tailings, these values may vary. In the modern tailing deposits (1973–1988) the values may reach up to 2370 μg g^{-1} for Pb and 2790 μg g^{-1} for Zn. However, on the older tailings, these values can be twice the amount of the modern ones, and in some cases even ten times higher (Table 1). The mineralogical assemblage also varies between the old and modern tailings. From a mineralogical point of view, all the tailings are generally rich in quartz, illite and kaolinite, but the older ones are also rich in sulfates on the surface, such as gypsum ($CaSO_4 \cdot 2H_2O$), jarosite ($KFe_3(SO_4)_2(OH)_6$), plumbojarosite ($PbFe_6(OH)_6(SO_4)_2$), argentojarosite ($AgFe_3(SO_4)_2(OH)_6$), anglesite ($PbSO_4$) and alunite ($KAl_3(SO_4)_2(OH)_6$). These sulfates are unstable chemical byproducts and are constantly subjected to precipitation-dissolution cycles during wet and dry conditions. This process can favor the loss of this mineralogical cement that keeps the material grains together, therefore enhancing the erosion of the tailings. This phenomenon plays a major role on the physical stability and geomorphic activity of the

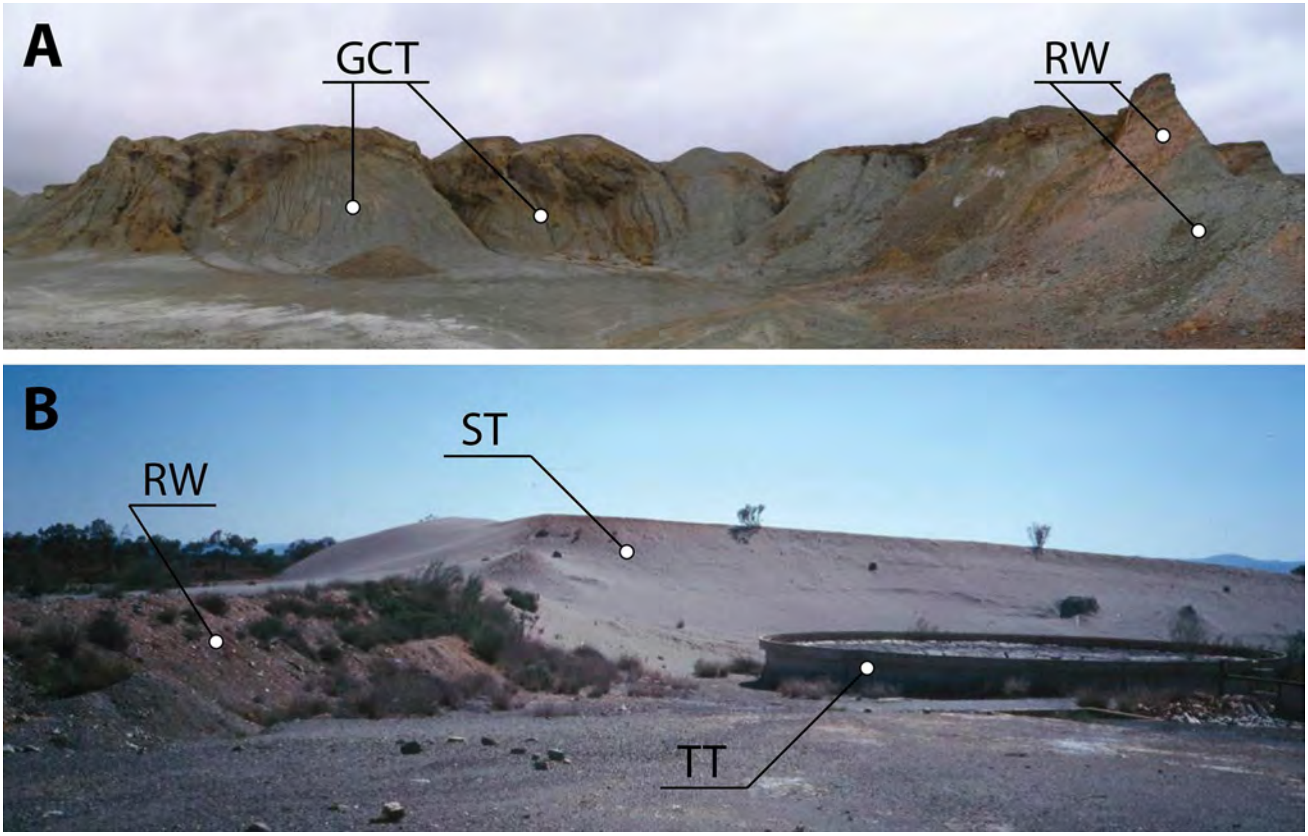


Fig. 3 **A** Lateral view of the old tailing deposits. These tailings generate acid mine drainage. *GCT* gravity concentration tailings, *RW* rock wastes. **B** View of the modern sandy tailings, rock wastes and the ruins of a thickener tank, a structure used to physically separate the solid fraction from a pulp or slurry made of a mixture of both solids and liquids. *ST* sandy tailings, *RW* rock wastes, *TT* thickener tank

tailings deposits (Martín Duque et al. 2015). This all has to do with the solubility product constant (Ksp), that is, the equilibrium constant for the equilibrium established between a solid solute and its ions in a saturated solution. If a salt undergoes dissolution e.g. $MSO_4 = M^{2+} + SO_4^{2-}$ (being M a divalent cation), then we shall have $Ksp = [M^{2+}]\ [SO_4^{2-}]$ (at 25 °C). Now, if the product of the concentrations of M^{2+} and SO_4^{2-} (expressed in moles per liter) become higher than Ksp, MSO_4 will precipitate. Thus, we face then a cyclic phenomenon in which rain water will contribute to the dissolution of the sulfate, whereas the evaporation of such water (during dry warm periods) will enhance the concentration of M^{2+} and SO_4^{2-}. Eventually, the dissolution will not be stable because $[M^{2+}]\ [SO_4^{2-}] > Ksp$ and therefore MSO_4 will precipitate. As expected, with the next rains the cycle will begin again. For example, in the case of gypsum (one of the salts in the tailings here discussed) this can be a strong mechanism contributing to the erosion of the tailings as the material loses coherence because the cement sticking the grains together is lost by dissolution. In fact, in a different but related context, gypsum is the cause of a geological hazard (gypsum karst) capable of swallowing houses and collapsing dams because this mineral dissolves readily in flowing water, which next to rivers can be at a rate about 100 times faster than that seen for limestone dissolution (Cooper 2006).

The instability of the tailings is further increased by the lack of any cover (either soil plus vegetation or just vegetation) protecting the surface from water erosion. The high metal content of the tailings acts as a limiting factor that restricts vegetation growth, allowing only the development of small shrubs and scattered plants. Nevertheless, some resilient plants grow on the modern tailings surface, including a small meadow of *Phragmites australis*, possibly due to a lower metal concentration.

Materials and methods

Geomorphic features within the San Quintín Mine site

Following the procedures described in Martín Duque et al. (2015), a field work campaign in February 2017 allowed the

Table 1 Heavy metals content for different soil samples on the San Quintín Mine site. Below appear the reference values for soils on the Ciudad Real province. Differentiation between old and modern tailings is done only for San Quintín East, as all the mine wastes on San Quintín West correspond to old tailings

	San Quintín East									San Quintín West		
	Modern tailings					Old tailings				Old tailings		
	1	2	3	4	5	1	2	3	4	1	2	3
Pb (%)	0.237	0.119	0.04	0.212	0.07	5.498	2.922	1.801	1.288	2.47	2.728	8.885
Zn (%)	0.279	0.119	0.03	0.146	0.13	1.020	0.383	0.265	1.516	3.807	3.251	2.545
Fe_2O_3 (%)	4.051	3.682	4.543	3.53	2.645	8.537	19.24	6.056	4.799	7.593	5.345	23.633
Mn (ppm)	619.3	454.7	604.8	412.2	332.9	542.8	42.35	341.1	689.9	426	484.9	32.2
Cu (ppm)	119.8	48.2	28.25	61.5	36.85	750.6	1415	344.7	110.9	405.2	115	3500
As (ppm)	17.4	33	< 3	< 3	32.3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Rb (ppm)	108.1	79.4	69	119.2	73.35	130.9	138.9	126.1	129.8	203.8	166.7	33.1
Sr (ppm)	39.35	57.1	135.9	42.4	44.5	63.55	55.4	60.95	70.05	59	139.4	17.75
Zr (ppm)	202	338.4	372.3	228.4	222.9	204.3	274.3	322.7	199.9	207.2	223.4	31.1
Sn (ppm)	74.9	63.8	75.1	51.4	40.35	91.1	133.8	111.7	106.5	117.9	128.7	< 68
Ba (ppm)	723.2	871.4	525.2	440.2	277.8	5050	4955	5235	1535	640.7	6115	606.5
Hg (ppm)	43.8	445.2	1245	68.1	486.7	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Cr (ppm)	55.7	55.8	144.6	55.3	< 30	57.85	52.6	57.55	66.8	92.25	83.95	67.6
Ni (ppm)	50.6	42	99.8	34.95	< 14	93.1	78.05	60.55	68.8	134.6	139.6	215.5
Sb (ppm)	79.6	< 65	< 65	< 65	< 65	505.85	221.05	108.5	173.6	366.3	189.8	1695
Cd (ppm)	< 25	< 25	< 25	< 25	< 25	28.7	< 25	< 25	< 25	306	174.7	< 25

	Pb	Zn	Mn	Cu	As	Rb	Sr	Zr	Sn	Ba	Hg	Cr	Ni	Sb	Cd
Reference Values (ppm)	44.2	86.5	–	27.0	16.1	234.7	1868.4	413.1	8.7	1049.3	–	113.4	42.6	5.7	4.4

reconnaissance of landforms displaying geomorphic activity at the abandoned tailings deposits of San Quintín and surroundings. We searched for unequivocal signs of current superficial dynamics, such as fresh incisions or scarps, along with the identification of landform types and patterns universally accepted in the geomorphic literature. The identified landforms were then process-based classified, described and genetically interpreted.

Quantification of the aeolian erosion

To estimate the aeolian erosion and transport rate on the modern tailings of the San Quintín Mine site, we first evaluated the direction, frequency and velocity of winds on the study area. To do this, we used meteorological open data recorded at the Ciudad Real Meteorological Station, 33 km away from the San Quintín Mine site, available from the Spanish Meteorology Agency website (AEMET). The available wind data account for the maximum wind-gust speed (in m s^{-1}) and directions (azimuth), registered for every month during 5 years (2012–2016) (Table 2). With this information, we managed to obtain a wind rose representing the maximum wind-gust directions and speeds around the study site. Furthermore, to evaluate the aeolian transport rate, we applied the modified O'Brien–Rindlaub model proposed by Dong et al. (2003). Numerous models have been developed throughout the years to estimate the wind particle transport (Sherman et al. 1998; Dong et al. 2003). Most of them can be classified in two different model types: (1) the Bagnold type models (Bagnold 1941) and its modified versions; and (2) the O'Brien–Rindlaub type models (O'Brien and Rindlaub 1936) and its modified versions. The main difference between these types of models relies on which are the parameters used to calculate the aeolian transport rate. The Bagnold type models directly relates the aeolian transport rates with the wind shear velocity, expressed as the root square of the shear stress of the surface material divided by the density of air (estimated 1.25 kg m^{-3}). On the other hand, the O'Brien–Rindlaub type models focus on the wind velocity on a given height. Usually, these types of models are easier to implement than the Bagnold type because the used parameters are easier to obtain.

Although the basic Bagnold and O'Brien–Rindlaub models have been proved useful on the prediction of wind transport rates (Bagnold 1941; O'Brien and Rindlaub 1936), they have some limitations. For sand particles to be mobilized by wind through saltation, it must reach a certain critical speed (threshold velocity), which varies according to the particles size. Given that the most basic models did not include this concept, different authors have developed

Table 2 Meteorological data related to maximum wind-gust speed (in m s^{-1}) and directions (azimut) registered by the Ciudad Real Meteorological Station during the last 5 years (2012–2016)

	Year 2012		Year 2013		Year 2014		Year 2015		Year 2016	
	Direct. (°)	Vel. (m s^{-1})	Direct. (°)	Vel. (m s^{-1})	Direct. (°)	Vel. (m s^{-1})	Direct. (°)	Vel. (m s^{-1})	Direct. (°)	Vel. (m s^{-1})
January	80	9.2	–	–	260	17.8	280	20	230	19.2
February	350	14.2	330	14.4	290	21.4	40	17.2	280	17.5
March	100	17.8	270	16.4	280	17.2	80	18.6	250	15
April	320	17.2	80	14.2	330	15	80	14.7	220	13.3
May	260	14.7	260	12.8	200	15.6	260	14.2	220	12.8
June	300	14.7	280	13.3	250	15.6	310	16.9	260	15
July	120	15.6	300	16.4	250	13.1	240	13.1	180	25.6
August	260	15.3	–	–	320	11.7	290	14.4	50	15.3
September	260	15.6	170	12.8	240	16.1	190	14.4	80	13.9
October	260	11.7	200	12.2	260	14.4	240	12.2	280	10.8
November	260	15.6	280	13.3	230	12.8	60	18.3	240	14.7
December	240	11.7	300	17.5	20	13.6	320	12.5	40	14.7
No. days $V > 15.27$ m s^{-1}	8		5		8		7		7	

a number of variations based on the original Bagnold and O'Brien–Rindlaub models to include the threshold velocity value on the wind transport equations (Kawamura 1951; Greeley and Iversen 1985; Lettau and Lettau 1978; Dong et al. 2003). Thus, in this work, we used the Dong et al. (2003) model, which is based on a reevaluation of the original O'Brien–Rindlaub one, where the wind transport rate is proportional to the square wind velocity at a given height corrected by: (1) a factor function of the particle size; and (2) the relation between the threshold velocity and the wind velocity at a given height. The modified O'Brien–Rindlaub type model proposed by Dong can be summarized on the next equation:

$$Q = f(d)(1 - R_u)^2 \left(\frac{\rho}{g}\right) V^3, \quad (1)$$

where Q is the sand transport rate, the sand flux per unit time and per unit width, in kg m^{-1} s^{-1}; $f(d)$ is a proportionality coefficient that varies with the particle size; R_u is the relation between the threshold velocity and the wind velocity at a given height (V_t/V); ρ is the air density, 1.25 kg m^{-3}; g is the acceleration due to gravity, 9.81 m s^{-2}; and V is the wind velocity at a given height.

The $f(d)$ factor has experimentally been proven to decrease with the particle size (Dong et al. 2003), following the next equation:

$$f(d) = 1/(475.25 + 93.62\, d/D), \quad (2)$$

where d is the given grain diameter, in mm; and D is the reference grain diameter, equals 0.25 mm. As said before, the wind threshold velocity is dependent of the particle size and the grain density. On ideal conditions, the estimation of the threshold velocity follows the next equation (Dong et al. 2003):

$$V_t = A'[gd(\rho_s - \rho)/\rho]^{1/2}, \quad (3)$$

where V_t is the wind threshold velocity; A' is a proportionality coefficient, with value 2.81 (Dong et al. 2003); g is the acceleration by gravity, 9.81 m s^{-2}; d is the grain size; ρ_s is the grain density; and ρ is the air density, 1.25 kg m^{-3}.

As the grain size and density are necessary for the application of the proposed model, we carried out a granulometric analysis of the materials affected by the aeolian processes, establishing the mass percentage of each granulometric fraction of a sieved sample, according to the USDA classification (2–1 mm; 1–0.5 mm; 0.5–0.25 mm; 0.25–0.1 mm; and 0.1–0.05 mm). The medium bulk density of the eroded materials was measured by the Blake (1965) method, using a dimension-known cylinder of 8.2 cm long and 8.2 cm in diameter. Each of the grain sizes were applied with the grain density value on the Eqs. (3) and (2), obtaining the $f(d)$ and V_t values belonging to the upper and lower limits of each granulometric fraction. These values were then processed to obtain a mean value representative of each granulometric fraction.

The mean values of $f(d)$ and V_t where applied to the Eq. (1) together with the mean wind velocity values for each of the identified wind directions. The obtained wind transport rates (Q) related to each grain size and wind direction where then statistically weighted with the mass percentage of each of the associated grain size, obtaining a weighted wind transport rate value (Q_w) for each grain size (that is, five different Q_w for each of the wind directions identified). Finally, the corresponding five Q_w where added together to make a general wind transport rate (Q_{total}) related to each one of the identified wind directions.

Results and discussion

Geomorphic features within the San Quintín Mine site

Overall, the mine tailings on the San Quintín Mine site share a similar range of geomorphic features that showcase the main external processes affecting the tailings materials. By means of a detailed inventory, we were able to identify a series of landforms produced by weathering, runoff-fluvial, aeolian and mass movement processes. Figure 4 compiles a selection of representative examples of the inventoried landforms.

Weathering landforms

Physical and chemical weathering are active processes acting on the exposed mine tailing materials on San Quintín, favoring its disaggregation, detachment and transport by other geomorphic agents and processes. The most common weathering landforms on the tailings are superficial popcorn crust layers. These present a cracked appearance, with little irregular aggregates of centimetrical width and depth (A in Fig. 4). The popcorn crust layers are interpreted here as the result of alternating wetting (swelling) and desiccation (shrinking) cycles related to chemical reactions of the unstable hydrated sulfates on the tailings. On the modern tailings, however, the wetting and drying cycles do not produce the popcorn crust layers. Instead, more polygonal desiccation cracks are generated, similar to the cracks occurring on muddy sediments (B in Fig. 4).

Runoff-fluvial erosion landforms

Runoff greatly alters the San Quintín landscape, forming rills, gullies, earth pillars, tunnel erosion (piping) and truly small-scale alluvial fans. Rills and gullies are the most visible landforms on the San Quintín minescape. Rills are small channels and grooves of few centimeters in depth and width, generated by the concentration of superficial runoff. Two types of rills can be differentiated in San Quintín. On upland surfaces, rills follow a dendritic pattern, while rills generated on steep slopes form parallel drainage lines following the maximum slope gradient. Almost all the rills on the San Quintín landscape appear on small waste dumps over the older tailings (C in Fig. 4), where their gentler slope prevents the development of greater erosional features.

Gullies are channels and grooves of several decimeters or meters in width and depth. Similarly to Brice's (1966) classification, here we differentiate two types of gullies according to the slope and location in which they develop: surface gullies and slope gullies. Surface gullies are linear incisions with vertical headwalls and steep slopes, characterized by intense erosion and with sufficient size to become permanent landforms of the landscape (D in Fig. 4). Some incision channels on the San Quintín tailings define examples of headward erosion, with various knickpoints along their courses (E in Fig. 4) and associated small plunge pools on its base. On the other hand, slope gullies develop a parallel drainage pattern favored by the high gradient on steep slopes, similar to those developed on natural badlands, but on a smaller scale (F in Fig. 4).

A network of small scale alluvial fans or dry washes develops on the flat base of the tailings and they spread several meters from there (G in Fig. 4). Similarly to real alluvial fans, those on the San Quintín Mine site present a granulometric gradation, with coarse materials on its head and gradually finer ones towards the external zones. These landforms only occur when there is a significant sediment delivery from upper zones. Where the sediment input is not enough to develop the small alluvial fans, a network of ephemeral channels of few centimeters width and depth develops (H in Fig. 4).

Miniature 'hodoos' and earth pillars of 30–40 cm diameter and height appear on flat surfaces and over the alluvial fans developed at the bottom of the tailings (I in Fig. 4). We interpret these landforms as the result of differential erosion acting on softer materials underneath a hardpan or a layer of more consolidated materials that protects the underlying sediments from raindrop impact erosion. The harder and more resistant caps may be the result of the tailings particles cementation caused by the chemical products on the tailings.

Piping or tunnel erosion processes occur on the San Quintín tailings both on upland surfaces and on the tailing slopes. Piping develops when subsurface flowing water preferentially circulates into fine-grained layers, removing soil particles and creating a subterranean drainage network (J in Fig. 4). We interpret the occurrence of piping processes in the San Quintín tailings as a consequence of the combination of two different factors. On one hand, the dissolution of unstable chemical products (sulfates and hydrated sulfates)

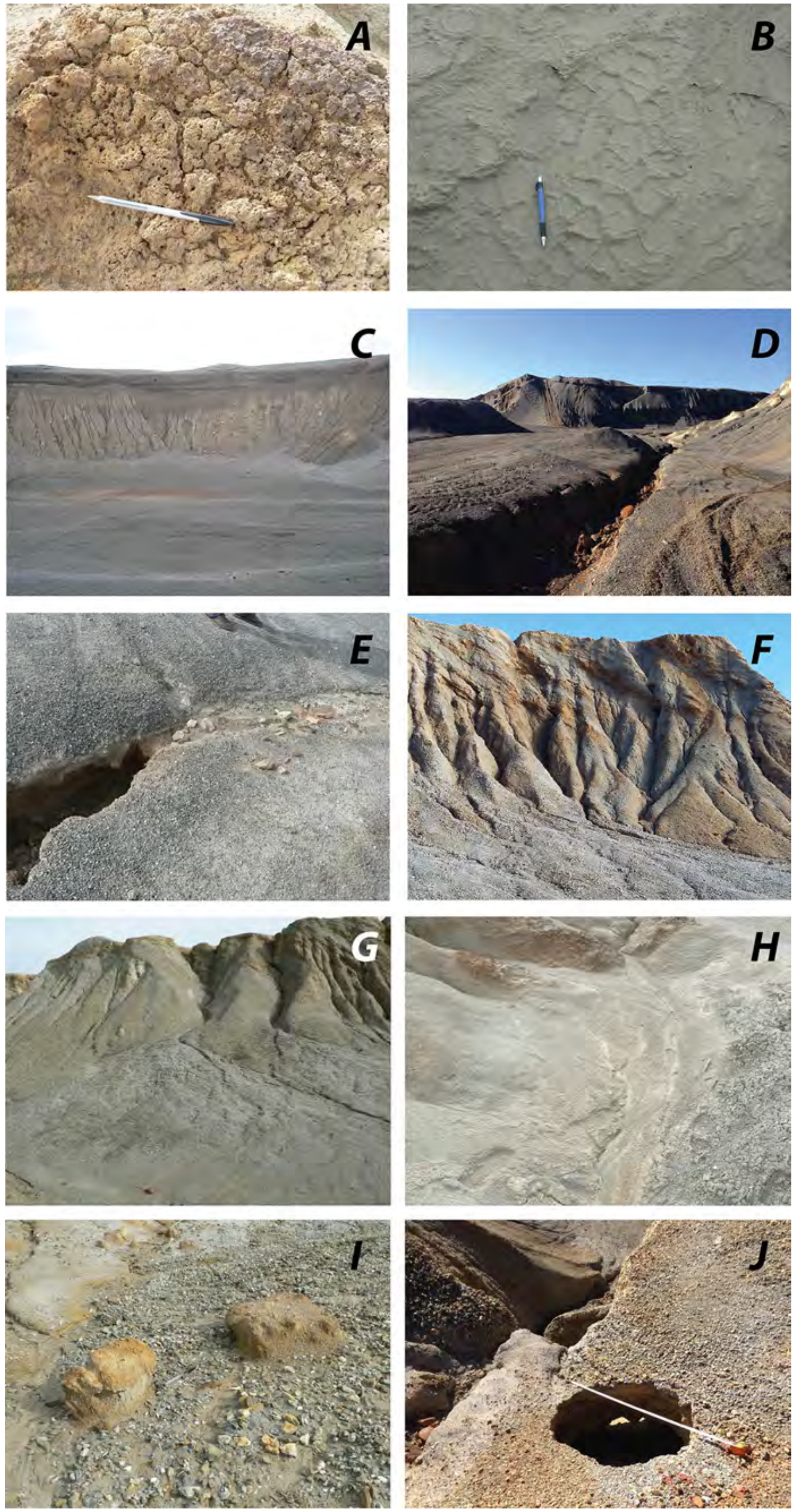
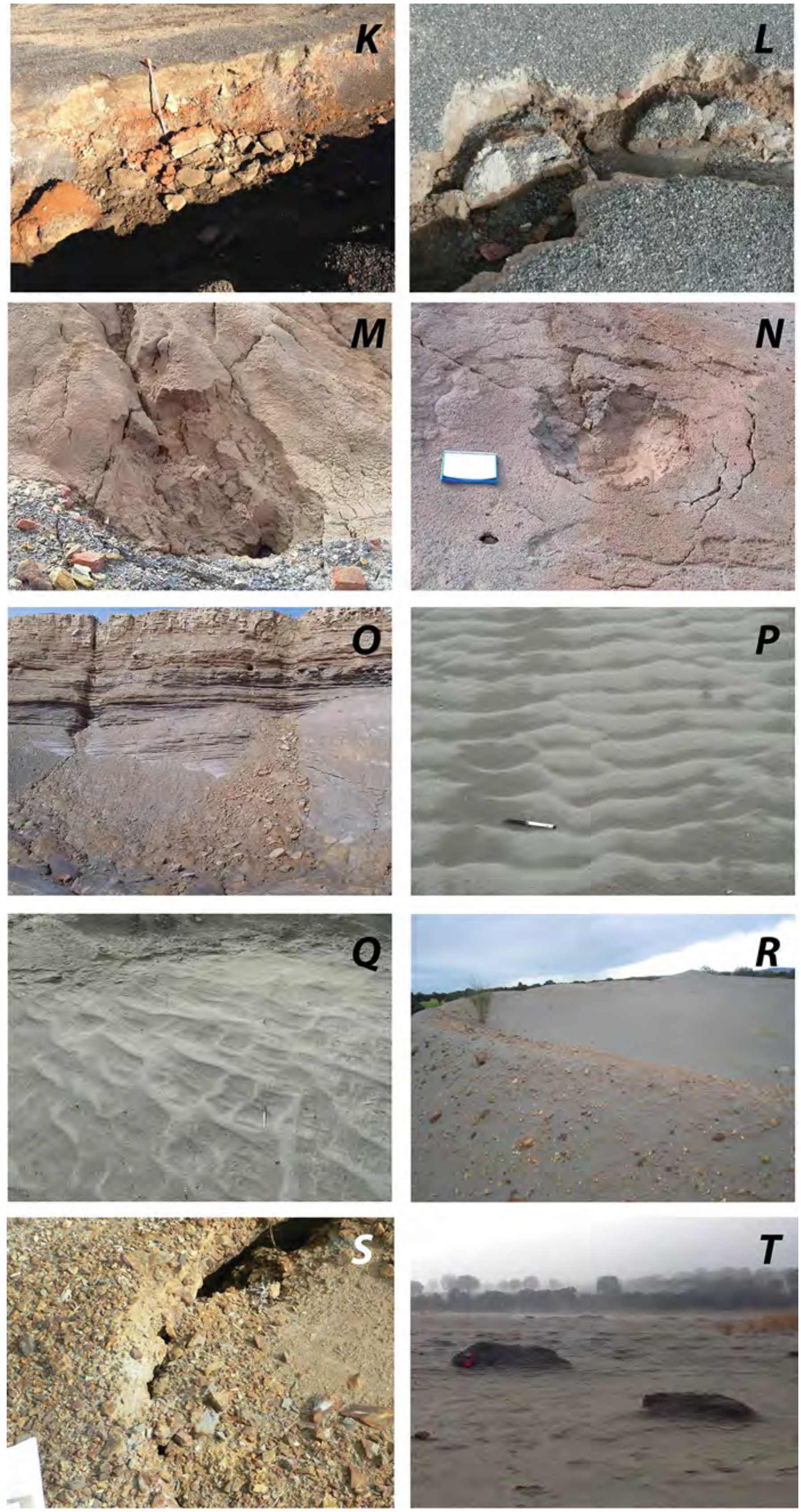


Fig. 4 Catalogue and classification of the main landforms denoting geomorphic activity at the San Quintín Mine site tailings. The numbers correspond with those scribed within the text. See text for detailed explanations of each landform

Fig. 4 (continued)



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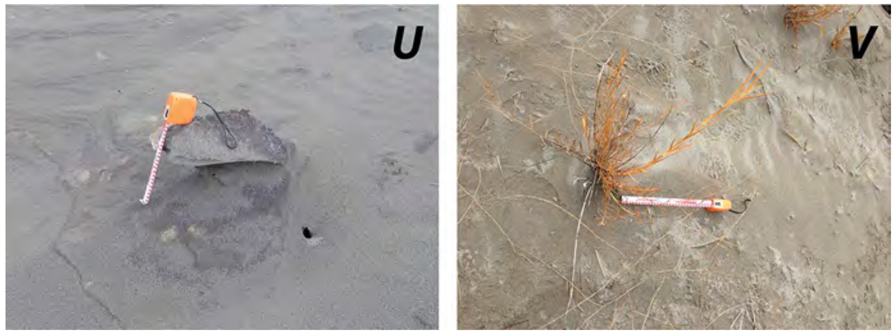

that act as cementation agent, makes the soil particle becoming loose materials, favouring its dispersion. On the other hand, the heterogeneous nature of the tailing materials, often accumulated in layers of different grain sizes and permeability, also favor the lateral circulation of subsurface water within the more permeable layers, defining a subterranean drainage network.

Mass movement landforms

The most common mass movement features within the San Quintín landscape are earth topples and earth falls. However, other mass movement landforms such as collapse sinks, subsidence and debris cones have been also observed. Both earth topples and earth falls are closely related to water erosion, as they generally occur on the steep walls of the upland gullies. In this respect, flowing water through upland gully channels actively erode the gully's bank bottoms, favoring the fall of the material above. The differentiation between earth falls and topples is based on the trajectory that follows the material on its fall, with a forward rotation around a point below its center of gravity for the earth topples (K in Fig. 4) and in a free-falling motion for the earth falls (L in Fig. 4). Collapse sinks are closely related to the subsurface drainage networks developed by piping processes. In some cases, the subsurface erosion causes the uppermost materials to collapse, forming cone shaped sinks or depressions similar to karstic ones (M in Fig. 4). When piping affects materials on the slopes of the tailing dams, it causes an increase of the slope instability and, therefore, favors the sliding of the tailings slope materials.

Subsidence occurs on upland surfaces, with a relatively quick sinking of the superficial materials due to the removal of the underlying deposits by subsurface erosion. Subsidence causes shallow circular hollows on the surface, up to a meter of diameter (N in Fig. 4).

Additionally, on some of the oldest tailings of San Quintín the waste materials are consolidated enough to form highly compacted layers of sediments. On the bottom of these tailings is common to see debris cones of various sizes, made by the fragments of consolidated layers of tailing materials (O in Fig. 4).

Aeolian landforms

The almost total lack of soil and vegetal cover on the surface of the San Quintín tailings alongside with their fine particle sizes makes them highly vulnerable to aeolian processes. A remarkable difference can be observed between the older and modern tailings regarding active geomorphic processes. While the former are almost devoid of wind-generated features, with only lag deposits, the latter, modern tailing deposits, show a great variety and number of different aeolian landforms such as wind ripples, blowouts, micro-yardangs and nebkhas (coppice dunes).

Ripples are centimetric aeolian bedforms that constitute the first response of sandy surfaces to wind transport. Ripples form when winds are strong enough to produce the saltation of sand grains that interact with irregularities of the surface. The windward side of the terrain irregularities is affected by the saltating sand grains, producing the mobilization of new particles and the accumulation of the collisional ones, generating a wave-like sand deposit (P in Fig. 4). Given that ripples generally form transverse to the wind direction, they serve as a clear cut indicator of the direction of particle dispersion by wind. In some cases, ripples form here with a more irregular shape, with intersecting crests. These kind of aeolian ripples are distinctive of the occurrence of two distinct wind directions interfering with each other (Q in Fig. 4).

Mobilization of sandy materials by wind on the modern tailings of the San Quintín Mine site can also be noticed by the presence of blowout depressions on the tailings surface (R in Fig. 4). These blowouts have an elliptical shape slightly stretched out on the wind direction. Blowout depressions usually form in response to a variety of factors such as reduction or loss of vegetation cover, topographic acceleration of airflow, climate change or human disturbances (Hesp 2002). On the San Quintín modern tailings, blowouts occur on the edge of the deposit presumably driven by topographic irregularities due to differences in the tailings grain size. We suggest that the tailing dam walls made of significantly coarser materials initially hampered the removal of sand by wind, whereas the adjacent inner tailings materials, composed by finer particles, where easily removed. The different erosion rate of both sediments started to create a topographic contrast between the tailings dam wall and the inner tailing materials, locally channeling and accelerating the wind flow towards the tailings lower sandy materials, thus leading to the formation of the blowout.

Wind deflation processes can produce the development of lag deposits on heterogeneous deposits in particle size, such as the San Quintín tailing dams. The wind action on the tailings surface cause the mobilization of the fine particles and leave behind the coarser grains that cannot be transported. The accumulation of coarser materials gradually form a layer on top of the deposits, protecting the finer particles beneath them from wind erosion. This type of aeolian landforms can be observed on the top surfaces of the San Quintín older tailings and in the modern tailing dam walls, where a coarse-grained layer is exposed to the surface (S in Fig. 4).

Yardangs are streamlined rocky formations carved on consolidated or semi-consolidated materials by the action of wind erosion and abrasion. A yardang resembles an inverted ship hull, with a blunt windward face that gradually gets narrower towards its leeward end. They can develop on a wide range of different lithologies, from semi-consolidated sediments to granites and highly resistant rocks, through abrasion and deflation processes (Gutiérrez Elorza 2009). Yardang-like structures appear on the upper surface of the modern San Quintín tailings. These formations, here called micro-yardangs, are considerably small, being only three meters long and one meter high in the best of cases (T in Fig. 4), but truly resemble those appearing in desert environments. We propose that the occurrence of these landforms can be explained by the combined presence of grooves (produced by superficial runoff on the tailings surface) and more consolidated materials or hard pans (favored by the chemical products of the tailings).

Similarly to the micro-yardangs, some mushroom-shaped structures appear on the upper surface of the modern tailings (U in Fig. 4). These structures are smaller than the micro-yardangs (20–30 cm long), and have a more resistant layer of materials, probably bound together by the chemical products of the tailings. Some coppice dunes or nebkhas also appear at the surface of the San Quintín modern tailings. These dunes, up to 30 cm long and few centimeters high, develop under the shelter of small plants of the genus *Phragmites* (V in Fig. 4). These structures serve as evidence on the extent of active aeolian processes that affect the tailing materials and can provide hints about the direction of wind particle dispersion.

Quantification of the aeolian erosion

The data extracted from the Ciudad Real Meteorological Station allowed developing a wind rose representative of the study zone. On that, we represent the wind-gust speeds with a 5 m s^{-1} interval (from 5 to 25 m s^{-1}), in conjunction with its direction and the percentage of occurrence of each possible speed-direction combination (Fig. 5). Two major wind directions can be differentiated from there. During all year long the most common winds near the study site are of WSW component (between 240° and 300°). These winds account for more than 45% of the total winds blowing near San Quintín and clearly represent the dominant wind direction. However, a secondary wind direction also develops during the year. These winds are of ENE component (around 80°) and although not as common as the main winds, represent almost a 10% of the total. The wind directions identified with the wind rose coincide with the aeolian landforms identified on the surface of the modern tailings. Both the aeolian deposits associated with the tailings and most of the micro-yardang structures agree with the dominant WSW component winds, whereas some landforms such as the coppice dunes or nebkhas coincide with the secondary, less common, ENE winds (Fig. 6).

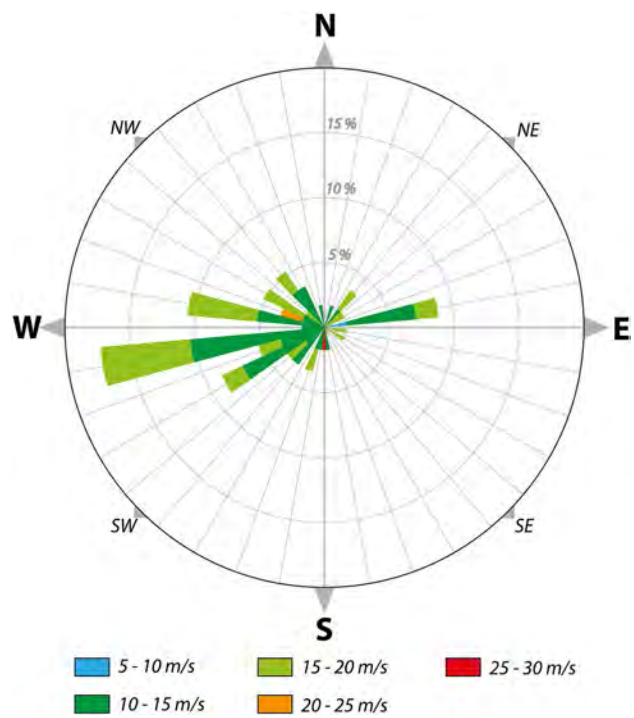

Fig. 5 Wind rose displaying the direction, frecuency and speed of winds blown near the study site, obtained through processing of the last five years meteorological data registered by the Ciudad Real Meteorological Station (AEMET 2017). Figure elaborated with Adobe Illustrator CS5

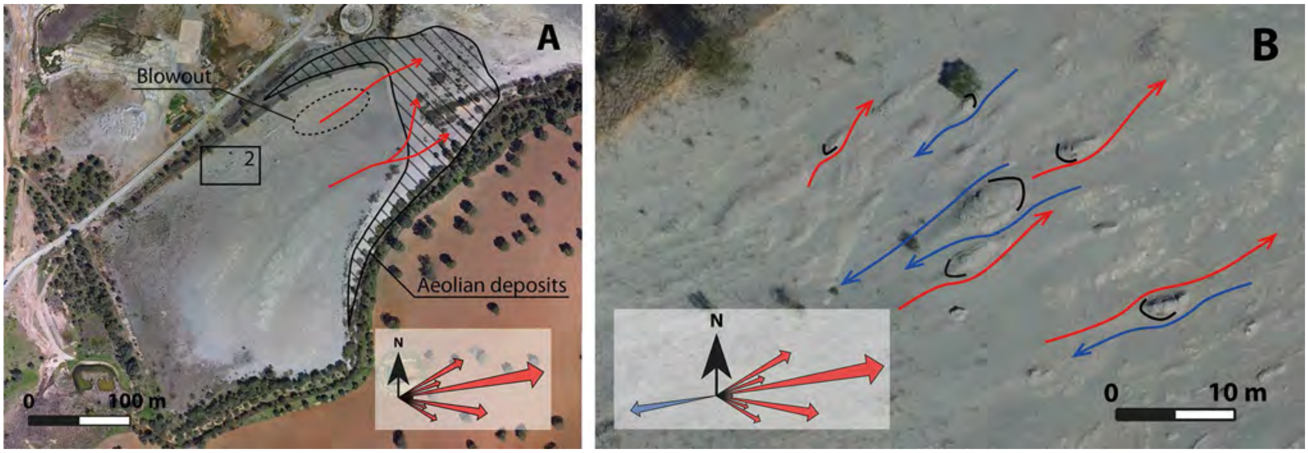

Fig. 6 **A** Aerial view of the modern tailings on San Quintín East. The aeolian deposits position coincide with the dominant wind direction around the study zone (represented by red arrows). **B** Detail view of the modern tailings surface, also showing the relation of the dominant wind direction (red arrows) and secondary wind direction (represented by blue arrows) with the position of the micro-yardangs and nebkhas developed on the tailings surface

As for the actual wind transport rate, we obtained two different values (Q_{total}), each one associated with the two identified wind directions: (1) an aeolian transport rate of 0.40 kg m^{-1} s^{-1} for WSW winds; and (2) an aeolian transport rate of 0.31 kg m^{-1} s^{-1} for ENE winds. To allow a comparison between the obtained rates and those related to fluvial erosion, we converted them to the same units (t ha^{-1} $year^{-1}$). Considering a medium width of 160 m for the modern tailings, a total surface of 4.8 ha, and the estimated time the wind-gusts are active on San Quintín during a year (approximately 7 days a year, 10 min each day), we obtained the following rates: (1) 56 t ha^{-1} $year^{-1}$ for WSW winds; and (2) 43.3 t ha^{-1} $year^{-1}$ for ENE winds. Taking into account that both wind directions are opposite, we can simplify the two estimated wind transport rates, obtaining a single net wind transport rate (equivalent to sediment yield) of 12.6 t ha^{-1} $year^{-1}$ related to WSW winds.

The obtained values only refer to high wind speeds and wind-gust events during a year, so they are not 100% accurate of the real wind erosion acting on the tailing materials. Also, these rates have been calculated with theoretical models referred to ideal conditions to provide an overview of the potential wind particle transport associated with certain wind speed and grain size. Thus, the obtained wind transport rate must be taken only as an estimation of the potential impact of aeolian processes on the San Quintín Mine tailings. Still, the impact of aeolian processes on the mobilization of tailings material comes close to the maximum wind erosion rates on Europe, of 15 t ha^{-1} $year^{-1}$, related to extreme events (Verheijen et al. 2009). These results led to the conclusion that the aeolian processes are a main geomorphic active process on the San Quintín Mine site, capable of delivering a considerable amount of contaminant mine wastes to the environment.

Tailings geomorphic instability and search for environmental solutions

The San Quintín Mine site landscape has a plethora of different landforms, as a result of the action of wind, water, chemical, and gravitational processes. These external agents have the ability to shape the tailings materials and cause its weathering, mobilization and deposition, thus making its understanding a valuable source of information for the design of effective mine rehabilitation and restoration measures. In this regard, the catalogue of landforms of the mine's tailings enabled to establish two main external processes controlling the tailings geomorphic instability: running water and wind processes.

This provides crucial insight on how the nature of the tailing deposits can directly condition their geomorphic evolution, and thus the amount of material delivered to the environment, once exposed to the external processes. As seen before, mostly all the runoff-fluvial erosional features have been developed on the old tailings, with little to no aeolian features, whereas the modern tailings present almost the exact opposite distribution, with no fluvial erosion features but numerous aeolian landforms. Here, we suggest that this heterogeneous geomorphic evolution between the two different types of tailings is intrinsically related to their physical and chemical composition. On one hand, the old tailings particle size heterogeneity hinders strong wind erosion, as they can quickly develop protective surfaces made by the exposed coarser materials as a response to the aeolian processes. This leaves the old tailings mostly subject to runoff-fluvial erosion. However, as the tailings geomorphology changes and fluvial landforms develop, the tailings gradually approach a more stable state, slowly reducing the amount of eroded material by fluvial processes. This is further enhanced by the old tailings high sulfate content, favouring cementation processes, and conditioning a low erosion rate of the San Quintín old tailings. On the other hand, the modern tailings have fine and homogeneous particle sizes, which leave them prone to be easily eroded by wind.

Once identified and evaluated the major processes involved on the geomorphic instability of tailing materials, the following proposed measures aim reducing both the aeolian particle delivery to the environment and the dispersal of heavy metals by acid mine drainage processes:

Wind erosion control measures would be the easiest ones to implement, and can be classified from less to more complex (and expensive) as it follows: (1) spread of a gravel cover on top of the modern tailings deposits; (2) direct revegetation of the tailings surface with local resilient plants species; although seemingly feasible, this measure can be tricky to implement due to the high pollutants content of the tailings; and (3) implementation of complex land covers that can both reduce the seepage of runoff and the capillarity ascent of water from the tailings deposits, together with soil and vegetal covers.

The acid mine drainage can be treated with a combination of two measures that have been proved useful on similar cases (Skousen 1998; Oyarzun et al. 2011a, b). They consist of the implementation of open limestone channels connected to constructed wetlands. Open limestone channels are capable of neutralizing the acidic flow streaming from the mine tailings, causing the precipitation of some metals such as Fe, Mn and Al (Skousen 1998), while the constructed wetlands may act on different contaminant elements depending on their development under aerobic or anaerobic conditions. Aerobic wetland can cause the decrease of heavy metal content by the formation and precipitation of oxides and hydroxides, whereas in anaerobic wetlands precipitation of sulfides occurs as a result of its reduction. Ideally, these acid mine drainage treatment measures should be located where they could collect most of the surficial runoff of the San Quintín Mine site, that is, the converging point of the mine's superficial drainage system. If one seek to maximize the efficiency of these remediation measures, constructing the open limestone channels following a meander-like shape would increase the circulation time of the acidic flow and thus favor the precipitation of heavy metals. A diagram of the proposed treatment measures in the San Quintín Mine site is provided in Fig. 7.

Conclusions

The study of landforms and geomorphic processes in the San Quintín Mine site provides new insights on tailings instability factors. A number of studies have been carried out on this landscape, focusing on the chemical leaching of metals from the tailings and their transport to the environment. However, none of them provides information about the actual physical instability of the tailing materials, thus leaving aside some key factors as weathering and erosion of the tailings. Our study is the first one that takes into consideration that issue in this mine site.

The elaboration of a detailed catalogue of landforms allows identification of a myriad of runoff-fluvial, aeolian and mass movement features throughout the entire San Quintín landscape. Landforms such as gullies, rills, miniature alluvial fans, collapses and tunnel erosion have been also catalogued, identified and interpreted on other decommissioned mine sites as a result of the tailings abandonment and exposition to external processes (Martín Duque et al. 2015). However, to the best of our knowledge, our study is the first to document, identify and interpret aeolian landforms developed on mine tailings. That, combined with the reduced size of this mining landscape, makes the San Quintín Mine site a world-class example on the impact of wind processes on mine tailings and adds considerable educational and geomorphic research value to the mine site.

The estimation of wind erosion rates has provided useful information about one of the main processes controlling the geomorphological instability of the tailings. The estimated wind transport rates for the modern tailings reach values similar to the maximum wind transport rates in Europe.

The old tailings of San Quintín, due to their material and particle size heterogeneity, are mostly subject to runoff and fluvial erosion. The modern tailing deposits, due homogeneity in particle size, are mostly prone to aeolian erosion. Because the availability of material is high, and no vegetation cover can spontaneously stablish here in these conditions of instability of the substratum, erosion is expected to be maintained with time. Also, due to the absence of gravel deposits, the landscape will not evolve towards a pavement desert type, with an end surface of gravel. Knowing that, efficient mine restoration and reclamation measurements on the San Quintín Mine site should focus, to a big extent, on reducing the effects of wind processes on the tailing materials together with the implementation of chemical remediation measures.

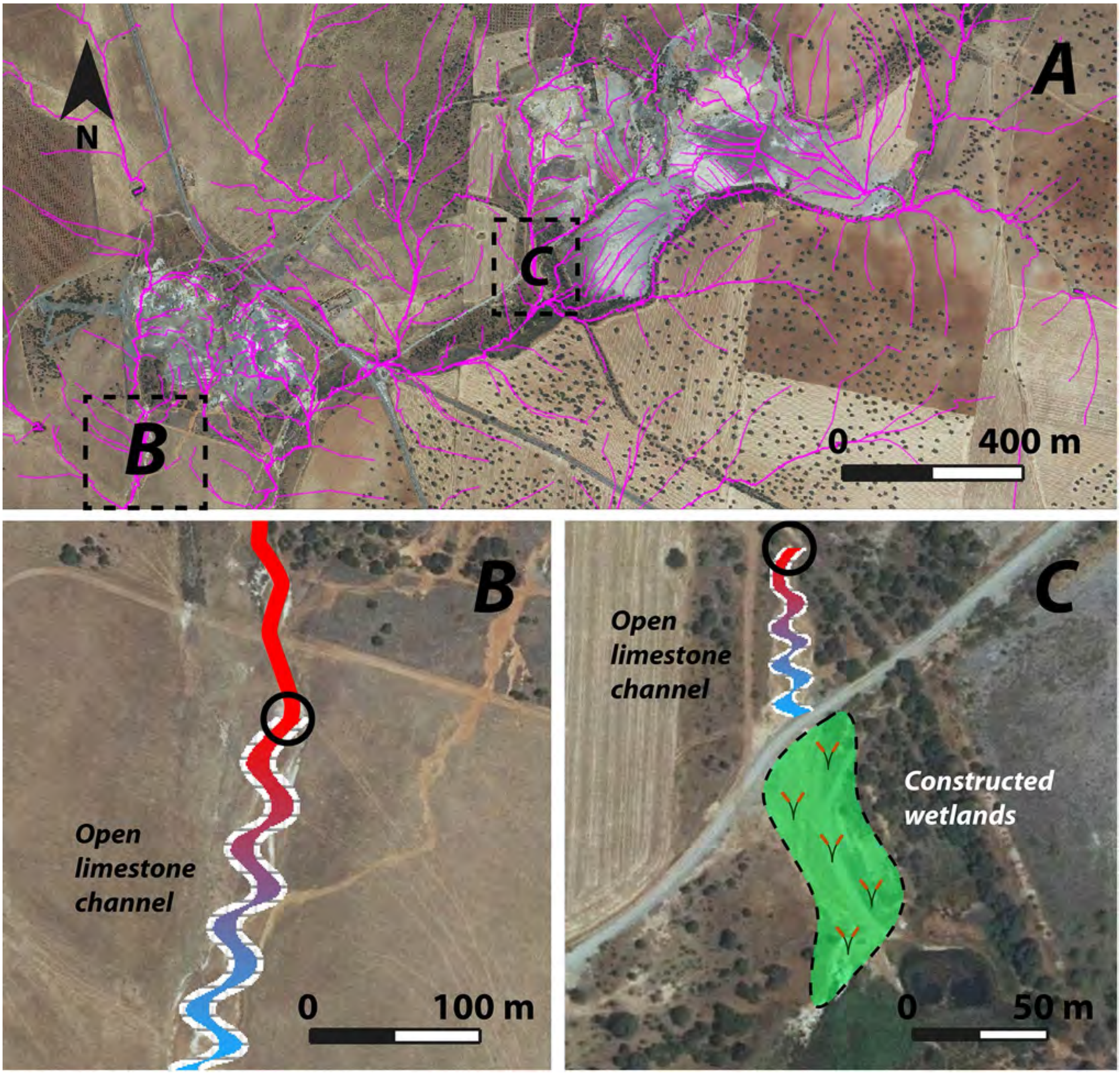

Fig. 7 **A** Ortophoto of 2015 (PNOA 2015), representing the drainage patterns on the San Quintín Mine site. **B** Detail of the proposed location of the open limestone channel on the San Quintín West complex. **C** Detail of the proposed location of the open limestone channel and shape of the constructed wetlands on the San Quintín East complex

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