Neogene basin infilling from cosmogenic nuclides ($^{10}$Be and $^{21}$Ne) in Atacama, Chile: Implications for palaeoclimate and supergene copper mineralization

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Abstract
Increasing evidence suggests that supergene exotic copper deposits were emplaced during periods of geomorphic quiescence and pulses of humidity in arid environments. We tested this idea in the Centinela Mining District in the Atacama Desert (northern Chile). We collected 14 sand samples at depth (up to 110 m) in two open-pit mines (Central Tesoro and Mirador) exposing Miocene sediment, and located in the El Tesoro Basin, which hosts two exotic copper-rich orebodies. We inverted the $^{10}$Be and $^{21}$Ne concentrations by using a two-box model (IMIS, inversion of multi-isotopes in a sedimentary basin) composed of an eroding source of sediment and a depositional sedimentary basin, and by selecting denudation and sedimentation rate histories that can explain our data. The ages found demonstrate that the two exotic orebodies were deposited during a narrow period between 14 Ma (10 Ma younger than previously thought) and 9.5 Ma, when an ignimbrite covered the sedimentary sequence. The dated lower exotic copper orebody was deposited during or just before a sharp decrease in the sedimentation rates (from >100 to 0.5–5 m/Ma), which is consistent with published sedimentological and carbonate isotopic data in this district. This confirms the idea that exotic deposits form during a quiescence of the geomorphic activity. Nevertheless, our model suggests that the back-ground denudation rate providing sediment to these basins between ca. 14 Ma and ca. 9.5 Ma was surprisingly high (>250 m/Ma) for such an arid environment. These denudation rates can be explained by a relatively rapid local back-scarp retreat providing most of the sediment to these basins and possibly a wetter climate compared to the present. Then, during the period 10–7 Ma, the denudation rates decreased to >50 m/Ma. This decrease may correspond to a local progressive decrease in the slope of the surrounding hills, or to a progressive aridification, or a combination of both phenomena.
1 | INTRODUCTION

The Atacama Desert in northern Chile and southernmost Peru hosts one of the world’s largest concentrations of world-class porphyry copper deposits on Earth (Sillitoe, 2010). Nearly all of these deposits show features related to supergene processes (i.e. mineralized near the Earth’s surface) that produce an increase in copper grades of the original hypogene mineralization through reduction–oxidation reactions occurring during weathering phases (e.g. Sillitoe, 2005). Copper can be mobilized by fluids in the lixiviation zone and then it can reprecipitate above the water table as oxidized minerals such as chrysocolla and atacamite or it can also be concentrated below the palaeo–water table as secondary sulphides (e.g. chalcocite and covellite). Fluids copper-bearing supergene fluids may eventually migrate laterally and transport copper up to several kilometres away from the weathered source of metal, until the copper precipitates form exotic copper deposits (e.g. Münger, 1996). Although the precise balance among precipitation, uplift and denudation rates for the generation of these deposits has not been quantified yet, the formation of supergene oxidized minerals is usually considered to have occurred during short and wetter periods in a context of an arid climate that dominated during the Neogene in the Atacama (e.g. Arancibia et al., 2006; Fernández-Mort et al., 2018; Palacios et al., 2011; Reich et al., 2009; Reich & Vasconcelos, 2015; Riquelme et al., 2018; Sanchez et al., 2018). Thus, understanding when supergene exotic oxidized minerals form is not only of particular interest to trace exploitable deposits but also to reconstruct past climates. Even though multi-approach studies tend to agree with the long-term aridity of the Atacama Desert, the timing of the hyperaridity onset is still matter of debate (see Figure 1 for a review and references).

Nevertheless, the effect of rainfall is ambiguous. An increase in rainfall favours leaching and the lateral transport of fluids from which oxidized minerals will precipitate. On the other hand, higher surface runoff favours erosion and, thus, removes the oxidized layer. Consequently, denudation of the porphyry copper system is a key process to understanding the formation of supergene copper deposits (Alpers & Brimhall, 1988; Braxton et al., 2009).

In the Centinela Mining District (Antofagasta region, Chile, Figure 2), recent sedimentological and thermochronological studies have confirmed that supergene copper mineralization related to porphyry copper systems formed during pedimentation periods in the Miocene corresponding to the waning of the Domeyko range with mean denudation rates in the order of 100 m/Ma (Riquelme et al., 2018; Sanchez et al., 2018). In this district, Fernández-Mort et al. (2018) evidenced the role of sedimentary environments in controlling exotic copper mineralization: copper minerals infilling the sediment porosity in beds truncated by erosion indicate that exotic mineralization has occurred during the sedimentation process near or at the surface under high evaporation rates, as expressed by C and O isotopy. Fernández-Mort et al. (2018) showed that some exotic copper mineralization forms in ephemeral distal lakes mainly by evaporation, whereas exotic copper deposited later mainly corresponds to the erosion of pieces of previously formed exotic copper deposits and their downstream deposition in sedimentary traps. Previous studies have suggested that low denudation and sedimentation rates are needed for the deposition of exotic copper deposits (e.g. Alpers & Brimhall, 1988) but the influence of pedimentation is still being debated (see discussion in Sillitoe, 2005). On the contrary, there has been no quantitative estimate of the porphyry copper denudation rate and sedimentation rate in sedimentary traps during the formation of exotic copper deposits.

Here, we take advantage of two open pit mines to sample a stratigraphic column hosting copper mineralization at great depths (>100 m). By measuring the $^{10}$Be and $^{21}$Ne cosmogenic nuclide concentrations and applying an original model to interpret these data, we draw the main lines of the post-14 Ma chronology in the Centinela Basin. Our work constrains the chronology of sediment deposition and the palaeodenudation rates. Denudation rate decreases from >500 m/Ma during...
**FIGURE 1** Onset of hyperaridity in the Atacama Desert. (a) Map of the Atacama Desert in northern Chile with study site locations and data type; the colours refer to the main morphostructural domain (CC: Coastal Cordillera, CD: Central Depression, PC: Precordillera, AS: Atacama Salar, WC: Western Cordillera, after Jordan et al., 1983). The red rectangle represents the Centinela District position. (b) Review of the aridity and hyperaridity onset timing inferred from various methods (method indicated in square in b); light grey for aridity and dark grey for hyperaridity

**FIGURE 2** (a) Location of the Centinela District via an oblique view of northern Chile in Google Earth. (b) Geological map modified after Riquelme et al. (2018). 1. Post–mid-Miocene poorly consolidated gravel deposits constituting the alluvial fans observed on the landscape surface. 2. Eocene mineralized porphyry intrusions (45–39 Ma). 3. Upper Cretaceous sedimentary and volcanic rocks. 4. Cretaceous and Palaeocene intrusions. 5. Jurassic calcareous rocks. 6. Upper Palaeozoic and Triassic basement. E. Esperanza gravels. TI, TII and TIII. Tesoro I, II and III gravels respectively. At. Atravesado gravels. Ar. Arrieros gravels
14–9.5 Ma to >50 m/Ma during 9.5–7 Ma. Moreover, our analysis indicates that copper exotic mineralizations occurred at specific times in a context of variable sedimentation rates. We discuss the implications of this scenario in terms of the regional morphological, tectonic and climatic history.

2 GEOLOGICAL BACKGROUND AND SAMPLING

2.1 Geological background

The Centinela Mining District is located at approximately 23°S, on the western border of the Precordillera physiographic unit (corresponding to the Domeyko range) of the Andean forearc (see location in Figure 1). The Precordillera is bordered by the Central Depression to the west and by the Atacama Salar to the east (Tomlinson & Blanco, 1997). In the district, several open pit mines have been developed: Tesoro Central, Tesoro NE (no longer in operation), Esperanza, Llano, Atravesado and Esperanza faults (Perelló et al., 2010; Sillitoe & McKee, 1996), complemented by ages dated from the Chuquicamata mine using U-Pb geochronological methods (Kahou et al., 2021). Altogether, these mineralizations ages range from 25 to 9 Ma, along with a few younger Pleistocene ages (Arancibia et al., 2006). A similar age range (22–18 Ma) has been found in the Centinela District using the \(^{40}\text{Ar}/^{39}\text{Ar}\) and K/Ar methods on supergene minerals (Perelló et al., 2010; Sillitoe & McKee, 1996), complemented by ages
in the range 25–13 Ma as reported by Riquelme et al. (2018). In the Tesoro NE pit, a single exotic supergene mineral age obtained in a copper-rich layer was dated at ca. 21.9 Ma. This age was first reported as a preliminary age by Tapia et al. (2012) and then by Oerter et al. (2016) and Riquelme et al. (2018). Riquelme et al. (2018) proposed that the layer bearing this age is a stratigraphic equivalent of the upper exotic copper orebody observed in the Tesoro Central mining pit (see location in Figures 2 and 3). These two deposits (Tesoro Central and Tesoro NE pits) are structurally separated by the Tesoro Fault (see Riquelme et al., 2018). There are no other published ages of supergene mineralization in the sediment of Tesoro Central.

2.2 | Geomorphic background: Denudation rates and palaeoclimate

As we will be discussing the denudation and sedimentation rates determined in this study, while focusing on the Centinela District, we first briefly report here the known denudation rates in the Atacama region, averaged over different periods and different spatial scales.

2.2.1 | Palaeodenudation rates

The long-term denudation rates in the Domeyko range (Maksaev & Zentilli, 1999) and in the Centinela District (Sanchez et al., 2018) have been determined by low-temperature thermochronology on intrusive rocks and Eocene porphyry copper deposits. These data suggest that most of the exhumation had occurred before 30 Ma at a rate on the order of 100 m/Ma, and that the denudation rates have dropped drastically since then (<10 m/Ma). Based on a compilation of thermochronological ages in the Atacama Desert, Arancibia et al. (2006) estimated that the denudation was less than 16–35 m/Ma from the Oligocene to late Miocene. Finally, Alpers and Brimhall (1988) determined that erosion rates on the order of >100 m/Ma enabled the exhumation of the La Escondida porphyry copper sometime between 33.7 and 18 Ma. They inferred that the
supergene activity between 18 and 14.7 Ma occurred while the
denudation rate was ca. 44 m/Ma. These authors postulated that
erosion dramatically decreased to less than 10 m/Ma after ca.
15 Ma due to the onset of hyperarid conditions. Elsewhere in
the Atacama region, the cosmogenic concentrations ($^{10}$Be) in
palaeo-riverine sediment were used to infer palaeo-catchment-
scale denudation rates. Ca. 400 km north of our study area,
Madella et al. (2018) determined that the palaeodenudation
rates range from 0.5 to 15 m/Ma for the 10.3–12.8 Ma period.
Finally, from an alluvial section from an area southwest of the
Salar de Atacama, Davis et al. (2014) determined a post-10 Ma
very slow sedimentation rate of ca. 3 m/Ma using $^{10}$Be and
$^{26}$Al, which is consistent with a very slow denudation rate re-
gionally for this period.

### 2.2.2 Catchment-scale and local-scale
denudation rates

In the Atacama region, several studies have estimated denu-
dation rates that were either averaged at the catchment scale
(>100 km$^2$) or corresponding to a local value (see review in
Carretier et al., 2018). The catchment-scale denudation rates
were estimated from measurements of the suspended river
load, and, in this case, correspond to the denudation rates aver-
ged over a decennial timescale. The denudation rates meas-
ured with cosmogenic nuclides in river sediments are averaged
over much longer timescales (from $10^3$ to $10^5$ years). The local
denudation rates were estimated from cosmogenic nuclides in
soils and integrate denudation over a period spanning from $10^3$
to $10^6$ years. At the catchment scale, in the Atacama Desert in
northern Chile (18–30°S), decennial denudation rates range
from 0.1 to 10 m/Ma with a notable exception in the Lluta River
(ca. 43 m/Ma, Carretier et al., 2018). The millennial catchment-
scale denudation rates derived from cosmogenic nuclides in
sand range from ca. 20 to ca. 80 m/Ma, and may reach 170 m/
Ma (Carretier et al., 2013; Cortés-Aranda et al., 2012; Kober
et al., 2009; Starke et al., 2017) (see Figure 4). The highest
catchment-scale denudation rate of 600 m/Ma was obtained
from $^{10}$Be in pebbles on steep slopes in the Aroma catchment,
ca. 400 km north to our study area (Carretier et al., 2019).

At a local scale, cosmogenic nuclides have recorded maximum denudation rates values in the range 0.01–50 m/
Ma in the Atacama region, with a median value lower
than 1 m/Ma (Amundson et al., 2012; Cortés-Aranda et al.,
2012; Dunai et al., 2005; Evenstar et al., 2009; Gattaceca et al.,
2011; Kober et al., 2007; Martinod et al., 2016; Nishiizumi et al.,
2005; Owen et al., 2011; Placzek et al., 2014; Ritter, Stuart,
et al., 2018). The currently observed low denudation rates may have lasted for
millions of years, without a significant change in relief
(Blard et al., 2019). Indeed, the development of gypsisoils
in the driest places of Atacama may provide evidence of
c. 10 Ma of hyperaridity and landform stability (rain-
fall <40 mm/yr, Rech et al., 2006): in the vicinity of
the Centinela district, this geomorphological stability is
further confirmed by the Artola ignimbrite dated at ca.
9.52 ± 0.02 Ma covering most of the landscape surface,
affected by minor reworking after deposition (Riquelme
et al., 2018), although this ignimbrite is vertically offset
(<100 m) by block uplift in the El Tesoro area.

### 2.2.3 Relationship among relief evolution,
denudation and supergene mineralization

As observed at the scale of the Atacama Desert (Arancibia
et al., 2006), the supergene mineral ages in the Centinela
district are 5 to 15 Ma younger than the main exhumation
phase (Sanchez et al., 2018), supporting the view that the
supergene exotic oxide mineralization occurred during the
waning of the topography (pedimentation), characterized by
lower relief and lower denudation rates than during the main exhumation period (Alpers & Brimhall, 1988).

2.3 | Sampling

A total of 14 samples were collected in the Centinela District, distributed in two different mine pits (nine samples from the Tesoro Central pit and five from the Mirador pit, see the location in Figure 3). In the Tesoro Central pit, samples were collected at depths between 65 and 135 m, with denser sampling within the lower copper-rich exotic orebody, at 106–115 m (see details in Figures 3 and 5). These sediments correspond to the Gravas I unit within the stratigraphic framework provided by Mora et al. (2004) or to the El Tesoro units in the framework given by Riquelme et al. (2018).

In the Mirador pit, sampling was performed at depths between 10 and 65 m (see Figures 3 and 5), both above and below the 9.5-Ma-old Artola ignimbrite, in the Arrieros unit according to Riquelme et al. (2018). Our goal here is to test whether the cosmogenic concentrations recorded the expected decrease in the denudation rates that could provide evidence for the hyperaridity transition in this period.

**FIGURE 5** Sedimentary columns of the Tesoro Central and Mirador open-pit mines with the sampling depths, gravel formation names and sedimentary details. The Tesoro Central column is after Fernández-Mort et al. (2018). Note that compared to Fernández-Mort et al. (2018), the column is truncated along our sampling path. The Mirador sedimentary column corresponds to our observations. The 9.52 ± 0.02 Ma age for the Artola ignimbrite has been measured by Riquelme et al. (2018)
3 METHODS BASED ON COSMOGENIC NUCLIDES

Measuring cosmogenic nuclides couples in ancient sediments permits to estimate their deposition ages and the palaeodenudation rates of the watershed from which they originate (e.g. Balco & Shuster, 2009; Davis et al., 2014; Puchol et al., 2017; Sartégou et al., 2018). Here, we develop an approach based on two cosmogenic isotopes, \(^{10}\)Be (radioactive, half-life 1.39 Ma) and \(^{21}\)Ne (stable). We collected 14 samples of nearly 500 g of fine-to-coarse sediment (granulometry between 0.5 and 5 cm) at each sampling point.

We developed a new two-box model (called IMIS, inversion of multi-isotopes in a sedimentary basin), in which one box is the eroding source of sediment and the other is the deposition basin. By considering various denudation and variable sedimentation rates (either fixed or random) in these two boxes, the model predicts the \(^{10}\)Be and \(^{21}\)Ne concentrations through time in the sedimentary sequence. Using a Monte Carlo approach, we minimize the difference between the predicted and measured concentrations to infer the best-fit scenario of denudation and sedimentation and to establish a modelled age for the sediment sequence. This approach also permits to derive the most probable deposition age for the sedimentary sequence.

3.1 Basic systematics

In situ cosmogenic nuclides are produced within the Earth's surface material through nuclear reactions (mostly spallation but also muonic capture) caused by secondary cosmic rays. Spallation processes occur within a couple of meters below the Earth's surface (e.g. Gosse & Phillips, 2001; Lal, 1991). The concentration of in situ-produced nuclides (i.e. produced within the crystal lattice) reflects the time the mineral spent in the production zone (ca. from the surface to a few meters below the surface). This is controlled by the date of exposure initiation, the local denudation rate and the local production rate (e.g. Bierman & Steig, 1996; Brown et al., 1995). Moreover, fluvial processes are assumed to produce well-mixed sediments, which are representative of the whole catchment. Assuming a steady-state topography, it is possible to use the concentrations of cosmogenic nuclides in detrital sediments to determine the catchment-wide spatial average denudation rate (Brown et al., 1995; Granger et al. 1996). In addition, as some of the cosmogenic nuclides are radioactive (e.g. \(^{26}\)Al and \(^{10}\)Be), a decay term must be considered, but it only slightly depends on the surface processes, when the denudation rates are less than 1 m/Ma.

Apart from the ‘simple exposure’ scenario resolved by a single nuclide, two cosmogenic nuclides can be analysed together to calculate the rock burial duration after having been exposed to cosmic rays at the Earth’s surface (Granger & Muzikar, 2001). This technique relies on the fact that two cosmogenic nuclides are similarly produced at the Earth's surface, when the production ratio is known. When the host minerals are buried, cosmogenic nuclides decay at different rates, therefore, their ratio changes with increasing burial time. This is most often achieved using the \(^{26}\)Al\(^{10}\)Be pair of cosmogenic nuclides (Balco & Shuster, 2009). The burial time \(t_b\) is given by Equation 1, where \(N_A\) and \(N_B\) are nuclide concentrations after burial, \(P_A\) and \(P_B\) are the respective production rates, \(\lambda_A\) and \(\lambda_B\) are the respective decay constants (value of 0 for stable nuclides) and \(f\) is the scaling factor at the exposure location (Blard et al., 2019).

\[
\frac{P_A}{N_A} e^{-\lambda_A t_b} - \frac{P_B}{N_B} e^{-\lambda_B t_b} = \frac{\lambda_A - \lambda_B}{f} \tag{1}
\]

For a detrital sediment sequence such as the one studied here, the cosmogenic nuclide concentrations in single clasts reflect a two-step history (Figure 6).

First, the preburial (initial) ratio of the paired nuclides \(R_{AB}(0)\) depends on the production rates and on the duration of the sediment residence in the source. \(R_{AB}(0)\) is acquired either during steady-state denudation rates \(\epsilon\) in Figure 6 or following a more complex exposure history in the uplands.
with successive temporary storage along hillslopes and along the river system (Balco & Shuster, 2009; Lal, 1991). Although transport durations of several tens of thousands years have been recently evidenced for large pebbles in a modern Atacama river (Carretier et al., 2019), the subsequent transport duration from the catchment to the sedimentary basin is generally not long enough for a significant concentration to build up. This preburial step, usually called ‘inheritance’, is fundamental as it produces the cosmogenic nuclide content of newly deposited sediments, which are used to decipher the history. In the case where some of the sediments underwent various cycles of exposure and burial, stable $^{21}$Ne records the preburial history in a more dramatic manner than radioactive $^{10}$Be. Finally, deposition within the sedimentary basin (at a rate $S_r$, Figure 6) leads to the second step of cosmogenic nuclide build-up, and this latter step is more important for low sedimentation rates (slower than the denudation). In the definition of $t_b$, it is assumed that the amount of cosmogenic nuclides produced during this step is negligible. This assumption may be wrong during the filling of the basins of the Centinela district: in this case, $t_b$ instead corresponds to a minimal estimation for the deposition time.

### 3.2 In situ cosmogenic $^{10}$Be and $^{21}$Ne sample processing and measurements

Samples were prepared using the standard procedures (see Supporting Information). Once pure quartz was obtained, the samples were split into two aliquots. The first one was used for the $^{10}$Be analysis, at Géosciences Environnement Toulouse (GET, France) and to the Accélérateur pour les Sciences de la Terre, Environnement, Risques (ASTER, Aix-en-Provence, France – except MIR-10, see Table 1).

The second quartz aliquot was used to measure the cosmogenic $^{21}$Ne concentration at the CRPG Nancy (France) noble gas laboratory (Table 2). During sample preparation, the grain morphology was checked. Bipyramidal grain shapes were observed. For instance, quartz minerals present bipyramidal shapes (Figure 7) in sample MIR13-01, just above the

| Sample | Mass quartz (g) | Carrier $^9$Be at | $N^{10}$Be | Measured $^{10}$Be/$^9$Be | Uncertainty measure + blank (%) | $[^{10}$Be$]$ at/g | $+/−$ |
|--------|----------------|-----------------|----------|--------------------------|-------------------------------|----------------|-------|
| **Process blank** | | | | | | | |
| All samples except MIR-10 | 1.93E+19 | 38 | 4.73E−15 | 16.29 | | | |
| MIR-10 only | 2.04E+19 | 41 | 5.41E−15 | 15.66 | | | |
| **El Tesoro** | | | | | | | |
| ET-01 | 67.35 | 2.39E+19 | 15 | 2.67E−14 | 25.86 | 7.817 | 2.021 |
| ET-02 | 62.13 | 2.41E+19 | 14 | 2.44E−14 | 31.75 | 7.630 | 2.423 |
| ET-03 | 66.51 | 2.39E+19 | 18 | 1.87E−14 | 29.98 | 5.030 | 1.508 |
| ET-04 | 68.28 | 2.40E+19 | 15 | 1.44E−14 | 26.70 | 3.378 | 902 |
| ET-05 | 59.82 | 2.41E+19 | 54 | 2.28E−14 | 14.45 | 7.288 | 1.053 |
| ET-06 | 6.19 | 2.37E+19 | 46 | 5.87E−15 | 26.77 | 4.337 | 1.161 |
| ET-07 | 13.31 | 2.38E+19 | 67 | 6.45E−15 | 12.30 | 3.059 | 376 |
| ET-08 | 57.76 | 2.41E+19 | 28 | 8.98E−15 | 18.95 | 1.774 | 336 |
| ET-09 | 19.66 | 2.38E+19 | 44 | 7.46E−15 | 15.50 | 3.298 | 511 |
| **AMS blank ET** | | 4 | 4.75E−16 | | | | |
| **El Mirador** | | | | | | | |
| MIR-01 | 12.35 | 2.38E+19 | 327 | 4.00E−14 | 5.71 | 68.021 | 3.887 |
| MIR-04 | 2.79 | 2.38E+19 | 1,202 | 8.17E−14 | 3.26 | 657,012 | 21,426 |
| MIR-05 | 3.70 | 2.38E+19 | 1,176 | 1.56E−13 | 3.32 | 969,755 | 32,215 |
| MIR-11 | 3.60 | 2.39E+19 | 30 | 5.50E−15 | 18.31 | 5,133 | 940 |
| **AMS blank MIR, except MIR-10** | | | | | | | |
| MIR-04$^a$ | 15.40 | 2.04E+19 | 71 | 8.67E−15 | 15.03 | 4.320 | 2,151 |
| **AMS blank MIR-10** | | 5 | 5.52E−16 | | | | |

Note: Final uncertainty is corrected for process blank, AMS standard and AMS systematic error.

*Sample prepared and measured at CEREGE.*
| Sample  | Mass quartz (mg) | Extraction temperature (°C) | [20Ne] × 10^6 at/g | +/- (1σ) | [21Ne]/[20Ne] +/- (1σ) | [22Ne]/[20Ne] +/- (1σ) | Computed cosmogenic [21Ne] for individual temperature steps +/- (1σ) | Computed cosmogenic [21Ne] +/- (1σ) |
|---------|-----------------|-----------------------------|-------------------|---------|-------------------|-------------------|---------------------------------|---------------------------|
| **El Tesoro** | | | | | | | | |
| ET-01  | 173.6           | 600                         | 3.3               | 0.1     | 0.00274           | 0.00010           | 0.10095                         | 0.00289                    | <DL                       |
| ET-02  | 173.6           | 1,400                       | 51.7              | 0.6     | 0.00288           | 0.00008           | 0.10130                         | 0.00248                    | <DL                       |
| ET-03  | 149.8           | 600                         | 7.6               | 0.2     | 0.00314           | 0.00008           | 0.10201                         | 0.00224                    | 1.8                       | 0.8                       | 8.8                       | 5.8                       |
| ET-04  | 149.8           | 1,400                       | 61                | 0.6     | 0.00302           | 0.00008           | 0.10055                         | 0.00245                    | 7                         | 5                         |
| ET-05  | 147.7           | 1,400                       | 41                | 0.5     | 0.00309           | 0.00010           | 0.10191                         | 0.00305                    | 8                         | 4                         |
| ET-06  | 185.5           | 1,400                       | 36.1              | 0.5     | 0.00629           | 0.00017           | 0.10181                         | 0.00287                    | 123                       | 7                         |
| ET-07  | 156.5           | 1,400                       | 32                | 0.5     | 0.00316           | 0.00012           | 0.10158                         | 0.00343                    | 8                         | 4                         |
| ET-08  | 105.6           | 1,400                       | 7.1               | 0.4     | 0.00386           | 0.00071           | 0.10560                         | 0.01955                    | 7                         | 5                         |
| ET-09  | 185.6           | 1,400                       | 31                | 0.5     | 0.00317           | 0.00011           | 0.10155                         | 0.00313                    | 8                         | 4                         |
| **El Mirador** | | | | | | | | |
| MIR-01 | 211.8           | 1,400                       | 44.5              | 0.6     | 0.00296           | 0.00008           | 0.10115                         | 0.00243                    | <DL                       |
| MIR-04 | 215.1           | 1,400                       | 2.8               | 0.4     | 0.00638           | 0.00122           | 0.10303                         | 0.02390                    | 10                        | 4                         |
| MIR-05 | 155.1           | 1,400                       | 5.1               | 0.4     | 0.02602           | 0.00335           | 0.12506                         | 0.02047                    | 118                       | 20                        |
| MIR-06 | 145.9           | 600                         | 0.1               | 0.1     | 0.00845           | 0.00298           | 0.08614                         | 0.06122                    | 0.7                       | 0.6                       | 137.7                     | 8.6                       |
| MIR-07 | 145.9           | 1,400                       | 38.4              | 0.5     | 0.00645           | 0.00019           | 0.10512                         | 0.00327                    | 137                       | 8                         |
| MIR-08 | 162.3           | 600                         | 3                 | 0.1     | 0.00297           | 0.00010           | 0.09969                         | 0.00314                    | <DL                       | 5.5                       | 21.4                      | 5.5                       |
| MIR-09 | 162.3           | 1,400                       | 59.3              | 0.7     | 0.00326           | 0.00008           | 0.10177                         | 0.00247                    | 21.4                      | <DL                       | 7.5                       | 21.4                      | 5.5                       |
| MIR-11 | 79.8            | 1,400                       | 4.3               | 0.1     | 0.00274           | 0.00013           | 0.09973                         | 0.00402                    | <DL                       | 7.5                       | 21.4                      | 5.5                       |
9.5-Ma-old ignimbrite (Riquelme et al., 2018). This crystal automorph shape suggests that it has a volcanic origin and was not transported over a long distance. MIR13-01 quartz minerals are likely to come from upstream erosion of the 9.5-Ma-old ignimbrite.

### 3.3 | Simple burial

Following the systematics of cosmogenic nuclides, it is possible to derive a simple burial duration knowing the present-day concentrations of two nuclides with different radioactive half-lives as well as the scaling factor $f$ (Equation 1). In practice, both the preburial exposure duration (or denudation rate) and the local production rate determine the preburial nuclides ratio, $R_{AB}(0)$ (Blard et al., 2019). However, when it is buried at low depth (<10 m) or shielded by a slow sedimentation rate (<10 m/Ma), the material is still exposed to cosmic rays. Hence, this results in an apparent burial duration ($t_b$) shorter than its real value. Burial durations computed with Equation 1 without any post-deposition correction, thus, yield an end member that is a minimum deposition time ($t_b$).

### 3.4 | Inversion

We developed an R (R Core Team, 2014) inversion program, called IMIS (available at https://github.com/regard-vincent/IMIS). It is based on a Monte Carlo approach, taking into account the evolution of the cosmogenic nuclide concentrations in a two-step clast history (Figure 6). The first step corresponds to the catchment denudation (box 1, Figure 6), neglecting the duration of the fluvial sediment transport to the basins. The catchment elevation is set to the current elevation of the basin. Sensitivity tests indicate this is not critical for our analysis. The catchment denudation rate is allowed to vary in the code but is fixed in the inversions as presented in the following. This step allows to estimate the nuclide concentration from Equation 2, where $P$ is the surface production, $\lambda$ is the decay constant, $\varepsilon$ is the denudation rate, $\rho$ is the density and $\Lambda$ is the attenuation coefficient; $i$ denotes the various production pathways, usually spallation and fast and stopped (negative) muons (see Braucher et al., 2011; Brown et al., 1995; Dunai, 2010; Granger et al., 1996; Heisinger, Lal, Jull, Kubik, Ivy-Ochs, Knie, et al., 2002; Heisinger, Lal, Jull, Kubik, Ivy-Ochs, Neumaier, et al., 2002). $P$ depends on the elevation of the source rock; the sensitivity tests showed that, in this context, potential changes in elevation did not significantly impact the results presented hereafter.

$$C = \sum_i \frac{P_i}{\lambda + \frac{\varepsilon \rho}{\Lambda}}$$

(2)

The second step corresponds to the sedimentation in the basin (box 2, Figure 6).

In our model, the basin infill is divided into periods, each being bounded by well-defined events such as the current surface, or in our case, the emplacement of the Artola ca. 9.5-Ma-old ignimbrite layer. A period is divided into various sub-periods with a random duration and a random sedimentation rate; the duration and thicknesses follow uniform laws, whereas the sedimentation rate corresponds to the ratio between thickness and duration. The number of sub-periods is arbitrarily fixed to seven, typically; this ensures an adequate level of complexity. The total sedimentation during a period is adjusted (by a multiplication ratio) to satisfy its stratigraphic thickness. The basement rock and sediment densities are set to 2,700 and 2,300 kg/m$^3$ respectively. Once a scenario has been drawn with its succession of sub-periods with specified sedimentation rates and durations, the model time is subsampled into time steps of 5 ka to compute the $^{10}$Be and $^{21}$Ne concentrations, as described in the following.

During each time step, we compute the concentrations of $^{10}$Be and $^{21}$Ne in two steps, first in box 1 and then in box 2. In box 1, the $^{10}$Be and $^{21}$Ne concentrations are calculated depending on their respective production rates at the elevation of the catchment, and the average catchment denudation (Equation 2). These concentrations are attributed to the newly deposited surface layer in the basin in box 2. At each time step, the $^{10}$Be and $^{21}$Ne concentrations in all of the deeper layers in the basin are updated taking both the decay of $^{10}$Be and the undersurface production of $^{10}$Be and $^{21}$Ne over the last 5 ka (duration of one-time step) into account. This production strongly depends on the production scheme. The production
at depth is often modelled with an exponential attenuation (although not for model HS, see below):

\[
P_i(z) = P_i(z=0) \cdot e^{-\rho z/\Lambda_i},
\]

(3)

Since there are different models describing the attenuation of \(^{10}\text{Be}\) and \(^{21}\text{Ne}\) production at depth that we explore in this study, we detail these models below. In the eroding areas (box 1), we only use one exponential attenuation scheme, while we use several schemes in the sedimentation area, called GH, BH, HS and BR (See Table 3 and Figure 8 for more details). The first letter stands for the \(^{10}\text{Be}\) production scheme: G for Granger and Muzikar (2001), B for Braucher et al. (2011) and H for Heisinger, Lal, Jull, Kubik, Ivy-Ochs, Neumaier, et al. (2002). The second letter is indicative of the \(^{21}\text{Ne}\) production scheme: H and S for Heisinger, Lal, Jull, Kubik, Ivy-Ochs, Neumaier, et al. (2002) and R for Braucher et al. (2011); \(^{10}\text{Be}\) production SLHL (sea level high latitude) is set to 4.15 at/g/a (Martin et al., 2017) and the \(^{21}\text{Ne}/^{10}\text{Be}\) ratio is 4.12 (Balco & Shuster, 2009; Kober et al., 2011). As we will see, the production parameter choice has a strong influence on the modelled concentration and subsequently on the misfit between the measured concentrations and their modelled values.

Once the \(^{10}\text{Be}\) and \(^{21}\text{Ne}\) concentrations have been updated, new \(^{10}\text{Be}\) and \(^{21}\text{Ne}\) concentrations are computed for box 1, which themselves are assigned to a new surface layer of box 2 and so on for the different time steps until the total duration of the modelled period is reached. This endpoint is reached when the basin is filled.

The procedure described above is run 5,000 times for different denudation and sedimentation scenarios in a Monte Carlo simulation. The best model parameters are then selected by minimizing the \(\chi^2\) misfit metric between the predicted and measured \(^{10}\text{Be}\) and \(^{21}\text{Ne}\) concentrations, defined by Equation 2.

\[
\chi^2 = \sum_i \frac{(C_{\text{obs},i} - C_{\text{mod},i})^2}{\text{Err}_i}
\]

(4)

In order to validate our inversion model, IMIS, we tested it on Davis et al.’s dataset (2014) from the Atacama Desert gravels near our study zone. It provides similar results to the inversions processed by Davis et al. (2014); see Supporting Information.

4 | RESULTS

4.1 | Concentrations

Concentrations (Tables 1 and 2) are comprised between \((6 \pm 4) \times 10^6\) and \((1.38 \pm 0.09) \times 10^8\) at/g for \(^{21}\text{Ne}\) (plus three samples that are below the detection limit) and are measurable for \(^{10}\text{Be}\) (from \((1.8 \pm 0.3) \times 10^3\) at/g to \((9.70 \pm 0.32) \times 10^5\) at/g), indicating that the minimum burial duration must be less than ca. 18 Ma (in the case where the initial concentration is high, >1 \times 10^6\) at/g for \(^{10}\text{Be}\), as in the present case), the time corresponding to the minimum detectable \(^{10}\text{Be}\) concentration (Tables 1 and 2). The homogeneity of the results makes the possibility of a complex history of burial and erosion unlikely, except for two samples with high \(^{21}\text{Ne}/^{10}\text{Be}\) ratios (>4,000, e.g. samples ET-04 and MIR-11, Table 4).

4.2 | Minimum deposition age from burial times

As a first level of analysis, we determine the minimum deposition age by assuming that once the sediments are

\[
P_i(z) = P_i(z=0) \cdot e^{-\rho z/\Lambda_i},
\]

where \(C_{\text{obs},i}\), \(C_{\text{mod},i}\) and \(\text{Err}_i\) are, respectively, the observed concentration, the modelled concentration and associated analytical uncertainty for the sample \# i. For each Monte Carlo set of inversions, we calculated three minimum \(\chi^2\) values, one for each single nuclide (the concentrations in Equation 2 are only \(^{10}\text{Be}\) or \(^{21}\text{Ne}\) ones) and one considering together the misfit for the two nuclides (\(\chi^2\) calculated on the entire set of \(^{10}\text{Be}\) and \(^{21}\text{Ne}\) data).

\[
\chi^2 = \sum_i \frac{(C_{\text{obs},i} - C_{\text{mod},i})^2}{\text{Err}_i}
\]

(4)

TABLE 3 | Cosmogenic production schemes derived from Granger and Muzikar (2001, GR), Braucher et al. (2011, BH and BR) and Heisinger, Lal, Jull, Kubik, Ivy-Ochs, Neumaier, et al. (2002, labelled H and for Neon production in GR, BR and HS)

| Beryllium-10 |  |  |  |
|---|---|---|---|
| Spallation | \(\Lambda\), Attenuation coefficient (kg/m²) | 1,600 |
| Muons | \(\Lambda\), Attenuation coefficients (kg/m²) | 7,380/26,880/43,600 |
| Surface production ratio (%) | 1.8/0.4/0.4 |
| Neon-21 | \(^{21}\text{Ne}\) to \(^{10}\text{Be}\) spallation production ratio | 4.12 |
| Spallation | \(\Lambda\), Attenuation coefficients (kg/m²) | H |
| Muons | Surface production ratio (%) | 0/3.6 |

Note: \(^{10}\text{Be}\) production SLHL is set to 4.15 at/g/a (Martin et al., 2017), and the \(^{21}\text{Ne}/^{10}\text{Be}\) ratio is 4.12 (Balco & Shuster, 2009; Kober et al., 2011).
deposited in the basin, they are immediately protected from further cosmogenic production by burial. This is obviously never true but this end-member model is useful to quantify a minimum limit for the sediment deposition age. Under this assumption (see Equation 1), the burial ages of the cosmogenic nuclides yield a minimum deposition age (see Methods), ranging from 6 to 18 Ma (Table 4). In the Tesoro Central pit (Figure 5), the obtained minimum deposition ages exhibit a smooth increase with depth, from ca. 11 (sample ET-02, ca. 59-m-deep) to ca. 13 Ma, 111 m below the surface (sample ET-08, see Table 4). The samples located near the main body of exotic copper mineralization display ages between 11 and 13 Ma (samples ET-05 to ET-08, see Table 4 and Figure 5). Sample ET-04 yields a minimum deposition age of ca. 17 Ma (Table 4). However, its $^{21}$Ne concentration is one order of magnitude higher than the concentrations of the other samples. This high $^{21}$Ne concentration suggests that the sample includes grains that underwent a long residence time close to the surface (either pre- or post-burial), where cosmogenic nuclide production is high. This leads to an overestimation of the burial time.

In the Mirador pit, the $^{21}$Ne/$^{10}$Be burial times reflect the stratigraphic order from ca. 7 Ma for the top samples (samples MIR-01 to MIR-05, see Table 4 and Figure 5) to ca. 14 Ma at a depth of 45 m below the surface (MIR-11, see Table 4 and Figure 5). The upper ca. 7 Ma samples stand just above the 9.5-Ma-old Artola ignimbrite, whereas the ca. 14 Ma sample is located dozens of meters below it (Figure 5).

4.3 | Palaeodenudation and sedimentation rates, determined by numerical inversion

In this section, we present the model inversion results that were used to test different sedimentation scenarios (Figure 9), each of which reflecting variable $^{10}$Be and $^{21}$Ne concentrations (Figure 10). In a first set of inversions, we fixed the denudation histories for Tesoro Central and Mirador.
First, for the Tesoro Central pit, the denudation rate is set to a low value (10 m/Ma) for the last 9.5 Ma (this value has little implication for the inversion), and to a higher value for the older stages. As suspected in the previous subsection, including the 21Ne concentration in ET-04 leads to a systematic worse fit ($\chi^2$ five times higher), indicating that no reasonable scenario can fit the 21Ne concentrations of this sample. Therefore, the 21Ne concentration in ET-04 was removed from the dataset in order to obtain the best-fit scenario. For these inversions, we first attempted to impose low denudation rates (50 m/Ma) but we found that the models for the Tesoro Central pit cannot fit measured concentration values for source denudation rates lower than 250 m/Ma for the pre-9.5 Ma period ($\chi^2 > 30$, whereas the best-fit $\chi^2$ ranges between 15 and 30, see Figure 11, Table 5 and Supporting Information). The modelled concentrations are most often too high compared to the observed data, requiring a higher denudation rate (smaller residence time in the source and, thus, smaller 21Ne concentrations, Figure 10). The best fit was equally good ($\chi^2$ ranges 15–30) for denudation rates greater than 500 m/Ma. Therefore, we use 500 m/Ma as a reference and we discuss this high denudation rate below. This set of inversions shows that 100 m of sediment was deposited between 14 and 9.5 Ma but during a shorter time period, potentially as short as 1 Ma, with sedimentation rates as high as several hundreds of meters per million years (Figure 9).

Secondly, we carried out inversions for the Mirador dataset. As most of our data are located above the 9.5 Ma ignimbrite, we carried out inversions for the last 9.5 Ma period, varying the sedimentation scenario and keeping the post-9.5 Ma denudation rate constant. We also tested different denudation rates. These inversions show that the best-fit scenario corresponds to a slow sedimentation rate of <2 m/Ma for the whole period and that the fit is better for denudation rates >50 m/Ma for the period 7–9.5 Ma ($\chi^2 < 150$, Figure 12 and Supporting Information). This inversion yields an age of 7 Ma for the deposition of the uppermost sample (Figure 12).

### 4.4 Additional constraints on the sedimentary layer hosting exotic oreibodies (Tesoro Central)

Our $^{10}$Be/$^{21}$Ne data burial times constrain the deposition age of the sedimentary layer hosting the exotic deposit in the Tesoro Central pit between 14 and 9.5 Ma. Moreover, the $^{10}$Be concentration clearly increases towards the layer top (115 to 105 m deep; Figure 10a) as does the $^{21}$Ne concentration (however, due to larger analytical uncertainties, this tendency is questionable for $^{21}$Ne, Figure 10b). This suggests either a slow sedimentation rate during the deposition of the sediment layer hosting the lower orebody of the Tesoro Central mineralization, or a hiatus just after its deposition: the $^{10}$Be best fits imply a sedimentation rate of ca. 0.5–5 m/Ma for the sediment layer hosting the lower orebody (see Supporting Information). This low sedimentation rate is imposed in the inversions by a peak in the $^{10}$Be concentrations near the top of this sediment layer (Figure 10). A low

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**TABLE 4** $^{21}$Ne/$^{10}$Be burial times (i.e. minimum deposition time, see text). Conc. refer to concentration (in atoms per gram, at/g).

| Sample | Depth (m) | $^{10}$Be concentration at/g | $^{21}$Ne conc. $\times 10^6$ at/g | Burial time (source elev = 2,500 m) Ma $^{10}$Be $+/−$ | Burial time (source elev = 4,000 m) Ma $^{10}$Be $+/−$ | Minimum erosion and sedimentation rate m/myr |
|--------|-----------|----------------------------|---------------------------------|-------------------------------|-------------------------------|------------------|
| ET-01  | 57        | 7,985                      | 3,273                           | <DL                           |                               |                  |
| ET-02  | 59        | 7,815                      | 3,968                           | 8.80 5.80 1.126               | 11.2 1.5 11.2 1.5            | 21.7             |
| ET-03  | 63        | 5,201                      | 2,619                           | 8 4 1.538                     | 11.8 1.4 11.8 1.5            | 19.0             |
| ET-04  | 84        | 3,545                      | 1,713                           | 123 7 34,699                  | 16.9 1.1 17.5 1.1            | 1.0              |
| ET-05  | 105       | 7,479                      | 1,786                           | 8 4 1.070                     | 11.0 1.1 11.1 1.1            | 15.3             |
| ET-06  | 106       | 6,156                      | 7,116                           | 7 5 1.137                     | 11.2 2 11.2 2.1             | 17.1             |
| ET-07  | 108       | 3,907                      | 1,899                           | 8 4 2.048                     | 12.3 1.4 12.4 1.5            | 16.7             |
| ET-08  | 111       | 1,973                      | 892                             | 6 4 3.042                     | 13.2 1.6 13.2 1.6            | 22.3             |
| ET-09  | 115       | 3,873                      | 1,790                           | <DL                           |                               |                  |
| MIR-01 | 18        | 68,021                     | 6,209                           | 10 4 147                      | 7.0 0.8 7.1 0.8             | 11.9             |
| MIR-04 | 13        | 657,012                    | 32,335                          | 118 20 180                    | 6.4 0.2 7.0 0.3             | 1.0              |
| MIR-05 | 12        | 969,755                    | 46,786                          | 137.7 8.60 142                | 5.8 0.1 6.4 0.1             | 0.9              |
| MIR-11 | 45        | 4,320                      | 2,057                           | 21.40 5.50 4,954              | 13.9 1.1 14.1 1.1            | 7.1              |
| MIR-10 | 63        | 5,133                      | 8,383                           | <DL                           |                               |                  |

Abbreviation: DL, detection limit.
sedimentation rate after the deposition of the sediment layer hosting the lower orebody is observed for 90%-100% of the $^{10}\text{Be}$ best inversion models (i.e. with varying erosion rates and production schemes); these conclusions are not sensitive to the muonic production scheme (Supporting Information).

5 | DISCUSSION

5.1 | Effect of assumptions on the calculated ages and rates

5.1.1 | Constant elevation and cosmogenic production rate

The analysis was performed for a source elevation of 2,200 m, similar to the current mining pit elevation. Nevertheless, it is possible that the source elevation above sea level was different at the time of deposition, in that it was either higher because the relief had decreased (Sanchez et al., 2018) or lower because this region may have been uplifted since then (e.g. Jordan et al., 2014; Riquelme et al., 2003). A <1,000 m difference in the elevation results in a <50% difference in the production rates. As a result, we consider our findings to be robust regardless of the initial elevation: the denudation rate thresholds discussed in the next paragraph are slightly offset towards higher denudation rates for higher source areas.

5.1.2 | Constant sediment density

The cosmogenic nuclide production in rocks and sediment depends on their mean density, as a higher density decreases the production rate. In our simulations, we assumed a constant density in the sediment, whereas different material and compaction may have generated density variations.

**FIGURE 9** Reference inversion for the El Tesoro mining pit (BR). (a) The colour corresponds to the $\chi^2$ value: light yellow to brown, where a darker colour is a better fit (lower $\chi^2$ value); the grey areas correspond to the improbable scenarios (too high $\chi^2$ values). The sample positions correspond to the ticks on the left; the copper layer is highlighted in turquoise. The inversion is constrained at three positions: arbitrary initial ($t = 20$ Ma, $z = -160$ m), ignimbrite layer ($t = 9.5 \pm 0.3$ Ma, $z = -10$ m) and surface ($t = 0$, $z = 0$). (b) Explanations of how to read this graph.
**FIGURE 10** Cosmogenic isotope concentration (reference inversion) according to depth (Tesoro Central), (a) for $^{10}$Be and (b) for $^{21}$Ne. For both figures, the light colours correspond to every Monte Carlo scenario tested. The bold lines represent the $^{10}$Be and $^{21}$Ne concentration pathways in panels a and b, respectively, that best explain (i.e. minimum $\chi^2$) $^{10}$Be only, $^{21}$Ne only and the data for both nuclides in blue, red and black respectively. The circles and associated horizontal lines indicate the measured concentrations and their related uncertainties. The black arrows indicate the increase in the concentration towards the top of the enriched copper orebody.

**FIGURE 11** Best $\chi^2$ for El Tesoro in function of the source area denudation rate for the period older than 9.5 Ma, for various production schemes for both nuclides ($^{10}$Be and $^{21}$Ne, logarithmic $\chi^2$-scale). The points indicate the best $\chi^2$ from the inversions, the trend is drawn as lines.
at depth. To evaluate the effect of sediment density on our results, we carried out simulations varying the density between 1,800 and 2,500 kg/m$^3$. These different density values do not significantly affect the calculated maximum age of 14 Ma for the studied sediment in Tesoro Central (see Supporting Information). The fit is slightly better for higher densities: the average $\chi^2$ value is ca. 25 for densities between 2,200 and 2,500 kg/m$^3$, whereas these values increase from 29 to 50 for decreasing densities between 2,100 and 1,800 kg/m$^3$ (Supporting Information). This is because a higher density limits the cosmogenic nuclide production in samples at great depth. In other words, models with a higher density better fit the low cosmogenic concentrations of the deeper samples.

The two pits investigated at Tesoro Central and Mirador are complementary at the regional scale and provide information about the history of the denudation/sedimentation rates (Table 5). Data from the Tesoro Central pit show three distinct periods, before 9.5 Ma ago. The first occurred sometime between 14 and 9.5 Ma ago; it corresponds to the sedimentation of layers that now host the lower orebody. The deposition of this layer was immediately followed by a second period during which the sedimentation was either slow (<5 m/Ma) or null. Then, there was a third period of rapid sedimentation (more than 50 m/Ma) of a material produced in a source area subject to high denudation (more than 250 m/Ma). This period was probably short, spanning roughly 1 Ma, the exact timing of which remains unclear (sometime between 14 and 9.5 Ma ago). The short duration of this episode of rapid sedimentation makes it compatible with the long-term averaged low denudation rates recorded in the area (16–35 m/Myr from the Oligocene to late Miocene; Arancibia et al., 2006). After 9.5 Ma (and before ca. 7 Ma ago), the source denudation rate and basin sedimentation dropped but remained significant, probably higher than 50 m/Ma. This is higher than what was observed by Davis et al. (2014) for the same period ca. 80 km to the south (1–10 m/Ma). In both pits, the sedimentation rate post-9.5 Ma is lower than 2 m/Ma, which is similar to what Davis et al. (2014) observed (Table 5).

Currently, the Centinela District is fed by a 2,041-km$^2$-wide catchment. The sediment deposition area spans 204 km$^2$, or one tenth of the catchment area. If all of the sediment was retained by the basin, its long-term sedimentation rate would be ten times the denudation rate. If a sediment bypass occurred, this rate should be less. Assuming that the feeder catchment has not changed much over the last 15 Ma, which seems reasonable for the Atacama, a catchment denudation rate as high as 250 m/Ma would have filled the Centinela District in a
very short amount of time (50 ka). This duration may be correct, corresponding to a very transitory stage; our data cannot rule it out. This duration could also be overestimated due to a smaller contributing area, as proposed below.

5.2 | High denudation rates for the Atacama

It is surprising that high (>100 m/Ma) denudation/sedimentation rates occurred after the lower exotic orebody deposition (sometime between 10 and 14 Ma BP) and before the 9.5-Ma-old ignimbrite, whereas hyperaridity was established (e.g. Dunai et al., 2005; Evenstar et al., 2009; Jordan et al., 2014; Oerter et al., 2016; Rech et al., 2006, 2010; Sillitoe & McKee, 1996). Sedimentation rates up to 100 m/Ma and denudation rates of more than 250 m/Ma are unexpected and have never been mentioned in the literature (Carretier et al., 2013), with the exception of the very rapid incision rate of the Loa River (Figure 2) in the Pleistocene (ca. 1,800 m/Ma; Ritter, Binnie, et al., 2018). For example, palaeodenudation rates deduced from $^10$Be concentrations in sediment from the El Diablo formation, 400 km north of our study area, have remained on the order of 1–15 m/Ma between 12.8 and 10.3 Ma ago (Madella et al., 2018). Yet, our findings appear robust with respect to different cosmogenic scaling schemes. Compared to long-term denudation rates, these values >250 m/Ma are still high. The thermochronological data provided by Sanchez et al. (2018) obtained in this area imply 2.5 to 3 km of denudation during the last 30–50 Ma (average denudation rates of 50–100 m/Ma). Considering that the denudation occurred mainly before 9.5 Ma ago (e.g. Arancibia et al., 2006; Riquelme et al., 2018), the average denudation rates deducted from the data of Sanchez et al. (2018) increase up to 150 m/Ma (denudation of 3 km during the period 30–10 Ma ago). One possible scenario for this high denudation rate is the occurrence of a wetter period before 9.5 Ma ago. In fact, Ritter, Binnie, et al. (2018) showed that river incision is strongly limited by the available water in Atacama. By dating a Pleistocene lake ca. 180 km to the north of the Centinela District, they found that the ca. 500 m incision of the Loa River occurred very rapidly in the last ca. 270 ka, during a wetter period. If the climate alone is responsible for our large palaeodenudation rates, then hyperaridity might have taken place in this particular area of the Atacama Desert at about 10 Ma ago.

A second possibility is that the sedimentation was constrained by fault activity. For example, Sanchez (2017) produced thermochronological data suggesting the activity of the nearby major fault to the west of the Atacama Salar (El Bordo escarpment, Figure 2), which was active during late Miocene (see location in Figure 2a). Late Miocene tectonic was also active elsewhere in Atacama (e.g. Allmendinger & González, 2010; Delouis et al., 1998). If late Miocene tectonic deformation occurred in the Centinela district, although not demonstrated, the expected denudation/sedimentation signal must have been transient, with fast denudation/sedimentation (typically >50 m/Ma).

To explain these high denudation rates, another hypothesis could be that the Centinela Basin records a regressive erosion wave during pediment emplacement (Figure 13). Based on sedimentological facies and detrital zircon provenance, Riquelme et al. (2018) proposed a pedimentation phase during late Miocene in the same area. The existence of persistent steep and elongated reliefs in the region, interpreted as back-scarp relief (Paskoff, 1977; Riquelme et al., 2018) suggests that the pedimentation process could have been proceeded by back-scarp retreat (Figure 13). Locally at the position of the back-scarp, where the topography is steeper, the denudation rates may be much higher than the average regional value (Strudley & Murray, 2007), providing most of the sediment delivered our study basins. This average regional denudation rate could, therefore, have been higher 10 Ma ago (see next section). A higher transient and localized denudation rate would be consistent with the strong slope control of the watershed denudation rate documented in Chile (Carretier et al., 2013) and elsewhere (e.g. Binnie et al., 2007).

5.3 | Hillslopes and tectonic activity drive late Miocene denudation

The timing of the onset of hyperaridity in Atacama has been extensively discussed based on sedimentological arguments (e.g. Hartley & Chong, 2002), surface exposure ages (e.g. Dunai et al., 2005) and supergene mineralization ages (e.g. Rech et al., 2009; Sillitoe, 2005). Based on the published literature, the proposed timing for the hyperaridification includes Oligocene to Pleistocene ages, and progressive-to-abrupt changes. Ritter, Stuart, et al. (2018) proposed that this debate can be reconciled by taking local climates in Atacama into account. According to these authors, the driest places may have undergone hyperarid conditions since late Miocene or even Oligocene, whereas other locations have been subjected to varying conditions with alternating arid periods and wetter local conditions. Our data show that, around 14–7 Ma, there was a decrease in the denudation rates of the hills in this part of the Atacama Desert that have provided sediments to the Centinela Basin. The average denudation rate decreased from >250 m/Ma between 14 and 9.5 Ma (Tesoro Central data) to >50 m/Ma between 9.5 and 7 Ma (Mirador data). Nowadays, these rates are much lower at <10 m/Ma (e.g. Placzek et al., 2010; Ritter, Stuart, et al., 2018). This decrease can be explained solely by the hills in the Centinela District having a lower slope (Figure 13). The pedimentation and progressively increasing distance between the source and the deposition area evidenced by Riquelme et al. (2018) during the Miocene must have been associated with a scarp retreat and relief decrease, as well as decreasing denudation rates. The slope is indeed a
decisive control on denudation in Chile (Carretier et al., 2018). This does not discard the possibility that progressive hyperaridification during the Neogene also contributed to the documented denudation decrease. Furthermore, the sedimentation rate dropped sharply after 9.5 Ma not only at Tesoro central but all over the Centinela District and beyond, to the south of it. As discussed above, local tectonic conditions controlling the accommodation space as well as the upstream variations in the source area may explain this decrease. Recent research on the eastern border of the Precordillera at the same latitude suggests that local exhumation occurred during the Mid-Miocene from which we can assume a reactivation of the drainage and a higher denudation rate (Sanchez et al., 2017). This does not discard the hypothesis that hyperaridification may played a role.

In conclusion, both geomorphological and climatic variations can explain our data. We cannot discard hyperaridification as a main driver, but it seems that, to explain our data, more evidence supports the hypothesis of a scarp retreat and pediment reworking.

5.4 | Dating of the sediment hosting the lower exotic orebody

In this framework, the Tesoro Central copper-bearing sediment unit is likely to be 10- to 14-Ma-old (Figure 9). It is important to note that this age cannot be much older, simply because there would be no detectable $^{10}$Be left in the deepest samples. This age is much younger than the age of ca. 21.9 Ma (Tapia et al., 2012) attributed to this orebody by lateral correlation (Oerter et al., 2016 citing Riquelme et al., 2018; Tapia et al., 2012) with another exotic orebody in the Tesoro NE pit.
found at a distance of 3 km (Figure 2). Our ages challenge this lateral correlation. They are also much younger than five other ages of supergene minerals in the same district dated between 19 and 25 Ma (Perelló et al., 2010; Sillitoe & McKee, 1996). On the contrary, our ages correspond to three ages of other supergene mineralizations dated between 15 and 12 Ma in the same district (Figure 2) (Riquelme et al., 2018). Our ages imply that the upper exotic orebody in Tesoro Central, above the one we dated, is younger than 14 Ma and older than the 9.5 Ma ignimbrite. The sediments hosting the lower exotic orebody that we have dated correspond to a particular stage in the geomorphological evolution of this region. This stage terminates with a low sedimentation rate period (preceding the episode of rapid sedimentation), for which the best inversions of the $^{10}$Be data give median values around 0.5–5 m/Ma.

6 | CONCLUSIONS

In this study, we have combined data from two cosmogenic nuclides ($^{10}$Be and $^{21}$Ne) in order to date and rate mid-Miocene denudation and clastic deposition rates with the aim to better understand the evolution of the late Miocene landscape and the conditions in which exotic copper deposits form in the Atacama Desert.

For the first time, we have proven that in situ produced cosmogenic nuclides (here the $^{10}$Be/$^{21}$Ne pair) are useful to provide constraints on the dynamics, age and conditions of an ore deposit formation: the studied exotic orebody deposited between 14 and 10 Ma ago, which is almost 10 Ma younger than previously reported by lateral correlation (Riquelme et al., 2018). Moreover, our results suggest that this exotic orebody emplaced during a low-deposition rate (quiescent) episode (sedimentation rate of the order of few m/Ma), probably promoted by a near-surface position under a high-evaporation setting (Fernández-Mort et al., 2018).

Our $^{10}$Be/$^{21}$Ne data also established the temporal evolution of the denudation rates in the area which dropped around 10 Ma, confirming in the Atacama Desert the onset of hyperaridity in late Miocene proposed by other authors. The current extremely low denudation rate (of the order of 1 m/Ma) has not been continuous for the last 10 Ma. Our data records a >50 m/ Ma denudation rate for the period ca. 7–9.5 Ma ago. The preceding period (roughly 9.5–14 Ma ago) recorded even higher denudation rates, of more than 250 m/ Ma, contemporaneous to sedimentation rates over 50 m/ Ma. The decrease in the post-14–9.5 Ma denudation rates records either a progressive aridification of the climate or a slope decrease associated with active tectonics or pediment development, or possibly both phenomena acting at the same time. Consequently, we do not recommend using our results to argue for a progressive (using the palaeodenudation record) or drastic (using the palaeosedimentation record) establishment of hyperaridity. Our data further support the hypothesis that 14–9.5 Ma was a crucial time for the evolution of the landscape in the western Central Andes and that this change (whatever it is, tectonic and/or climatic) was concomitant with the occurrence of copper mineralization.

The success of our analysis was probably favoured by the local large thickness (>10 m) of the sedimentary deposits, allowing for more detailed records than elsewhere within the regional framework. Although sediments older than 10 Ma have only rarely been used for cosmogenic nuclide analyses, our work shows the potential of cosmogenic nuclides and helps push the limits of this technique, following recent improvements (e.g. Davis et al., 2014; Madella et al., 2018; Puchol et al., 2017; Val & Hoke, 2016). The $^{10}$Be/$^{21}$Ne couple is particularly useful to date sediments and to estimate palaeodenudation rates from material older than 10 Ma (Sartégo et al., 2018, 2020).

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PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are found in the core of the paper, except the code IMIS, openly available in GitHub at https://github.com/regard-vincent/IMIS.

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