Reviewers' comments:

Manuscript ID: egusphere-2025-4801

Title: " U-Pb dating of chrysocolla from supergene copper deposits in the Coastal Cordillera of northern Chile, Atacama Desert"

We sincerely thank the reviewers for their thoughtful and constructive comments. Below, we provide a detailed, line-by-line response to each point raised. For clarity:

- Reviewer comments are shown in italics.
- Our responses follow immediately after each comment in grey colour.
- All corresponding changes have been incorporated into the revised manuscript, where modifications are marked for easy reference.

Reviewer Comment 2: Laura Evenstar 20.12.2025

This paper examines the dating of chrysocolla in supergene-enriched deposits located in the Coastal Cordillera of Northern Chile at three different sites ranging from 22 to 24.30 degrees latitude. The authors utilise U-Pb dating of chrysocolla from various locations, and at each location, the altitude differs in the samples collected. The results indicate a range of ages for the formation of Chrysocolla from 8.4 million years ago (Ma) to 0.005 million years ago (Ma). The ages appear to vary more with altitude than with latitude, with older ages found at higher altitudes and the majority of younger ages located below the current fog level. As a result, the authors conclude that recent supergene enrichment in the Coastal Cordillera is related to the occurrence of fog from the coast.

The paper is well-written and features excellent figures. I recommend publication after making some modifications to the main narrative, specifically to clarify the discussion surrounding climate and the differences between meteoric and groundwater-sourced supergene processes. Additionally, some minor edits should be implemented throughout the rest of the manuscript.

Comment 2.1: *The discussion regarding the climate in the study area needs to be clearer and more concise. Instead of suggesting that the hyperaridity in the Atacama had a singular onset, it should be noted that multiple authors have documented alternating periods of wetter and drier conditions since the Miocene. The cyclical nature of dry and wet phases resulted in multiple episodes of supergene mineralisation, sedimentation, and surface formation. It is essential to emphasise that the studies often date climatic fluctuations rather than identify a specific moment when aridity began. This clarification will help explain the variations in ages presented in Figure 1. Although this point is mentioned in the discussion, it would be more explicit in the introduction*.

Response 2.1: We believe that the introduction already clearly states that previous studies propose different timing for the onset for the hyperaridity. Nevertheless, we have added a clarifying statement to further emphasize these differences. We extended our introduction paragraph and outline in more detail the paleoclimate evolution and in particular its variability in the Atacama Desert regarding the repeated activity of supergene processes. Moreover, we added a short statement about recent moisture sources, by rain or fog, which might temporally provide enough moisture to restart supergene processes, even on only a small scale.

We changed the introduction paragraph Line 34 to 41:

"Climate variability caused repeated shifts in the occurrence and availability of precipitation in the Atacama Desert during predominant hyperarid conditions since the Miocene (Dunai et al., 2005; Evenstar et al., 2009, 2017; Jordan et al., 2014; Ritter et al., 2018a). Nevertheless, based on previously reported supergene copper ages, these shifts and associated phases of supergene activity are largely Miocene in age (Sillitoe and McKee, 1996; Hartley and Rice, 2005; Arancibia et al., 2006; Reich et al., 2009; Evenstar et al., 2024). This suggests that since the Middle Miocene, the overall climate of the Atacama Desert has remained below the precipitation threshold required to initiate supergene activity. However, at an altitude below ~1200 m a.s.l., the Coastal Cordillera is influenced by coastal fog (Schween et al., 2022), which may provide sufficient local moisture to reactivate supergene processes."

__Comment 2.2:__ *The manuscript should more clearly distinguish between meteoric-water-dominated supergene enrichment and groundwater-dominated supergene mineralisation. Meteoric-water-controlled supergene enrichment represents a hydrologically open system characterised by the sustained downward percolation of rainfall, vertical copper transport, and precipitation occurring near the water table. This process is dependent on climate and can be associated with specific precipitation thresholds, such as approximately 120 mm per year. Consequently, K-Ar dating of alunite can be used to examine variations in arid and semi-arid climatic conditions, as the formation of alunite is linked to the circulation of meteoric fluids.*

Groundwater-dominated supergene systems are hydrologically constrained, meaning that copper is redistributed locally within the oxidation zone by saline groundwater, capillary fluids, or evaporated brines. This redistribution can occur without the need for meteoric recharge to the water table and is not limited by the approximately 120 mm/yr precipitation threshold. Chrysocolla formation, as I understand it, is primarily influenced by solution chemistry under oxidising conditions and can develop in both meteoric and brine-dominated supergene environments. Consequently, using it as a direct climate proxy is problematic. This distinction is important for interpreting the climatic significance of the mineral assemblages discussed in the paper and could be explained more clearly in the text.

Response 2.2: We agree that the formation of supergene copper minerals (not supergene enrichment) is primarily controlled by the circulation of meteoric waters within hydrologically open systems. These systems are dominated by rainfall percolation, with copper mobilization and redistribution governed by local rock permeability (e.g., porosity and fracture networks). This meteoric-water–controlled setting is characteristic of small, local catchments and shallow circulation systems such as those developed in the study area. In this context, meteoric-water–dominated systems are characterized by downward infiltration of rainfall and lateral redistribution of copper near the surface.
Groundwater-controlled supergene processes, by contrast, do not necessarily imply hydrologically closed systems. Copper may also be transported by groundwater under open-system conditions; however, groundwater influence is typically associated with more regional-scale flow systems and distinct hydrochemical signatures. A specific and fundamentally different case is the localized inflow of saline groundwaters, which has been shown to trigger the precipitation of atacamite through replacement of earlier supergene minerals such as chrysocolla (e.g., Kahou et al., 2021). This process has been documented at Mina Sur (Dold et al., 2023) and at the Spence, Gaby Sur, and Radomiro Tomic deposits (Cameron et al., 2007). Both deposits are influenced by and hydrologically connected to precipitation sourced from the higher Andes to the east of our study area, which were capable of providing sustained groundwater.

In the present study area (Coastal Cordillera), however, catchment sizes are too small and are not hydrologically connected to higher precipitation catchments to support a significant role for regional groundwater systems in the formation of supergene copper minerals. As pointed out by Maureira et al. (2022), supergene mineralisation hosted in the Coastal Cordillera is controlled by meteoric waters. Consequently, rainfall-derived meteoric water is interpreted as the dominant fluid and process driving supergene mineralization in the Coastal Cordillera. Moreover, a hydraulic connection with inland groundwater systems from the Andes or the Central Depression is highly unlikely, given the location on the western flank of the Coastal Cordillera, at elevations of approximately 2,000 m above sea level, being generally higher than the Central Depression.

In the revised manuscript, we describe now the catchment-scale hydrological setting of the study area and clarify the distinction between meteoric-water–dominated and groundwater-dominated supergene processes. We now emphasize that, due to the geographic and geological position of the sample sites within the Coastal Cordillera, large regional groundwater systems sourced from extensive catchments receiving sufficient precipitation—such as groundwater systems of the Central Depression and Precordillera fed by Andean precipitation are not representative of the sites investigated in this study.

We modified the following in the revised manuscript:

Line 54-64: “Water availability for supergene mineralisation may be provided by two principal sources: 1) meteoric waters derived from precipitation (Vasconcelos, 1999; Chávez, 2000; Hartley and Rice, 2005) and 2) groundwater sourced from large, regional hydrological systems (Ague and Brimhall, 1989; Cameron et al., 2007; Shaw et al., 2021). In the Coastal Cordillera, including the present study area, the limited size of catchments, low precipitation, generally low permeability and elevated topographic position preclude the development of a sustained regional groundwater system comparable to those of the Central Depression or Precordillera (Herrera and Custodio, 2014), where groundwater-fed supergene mineralisation has been documented (e.g., Mina Sur: Dold et al., 2023; Spence, Gaby Sur and Radomiro Tomic: Cameron et al., 2007). Consequently, supergene mineralisation in the Coastal Cordillera is controlled by meteoric water availability, as previously demonstrated by Maureira et al. (2022). Therefore, chrysocolla in the copper deposits hosted in the Coastal Cordillera precipitates from meteoric waters (Crane et al., 2001; Palacios et al., 2011; Kahou et al., 2021; Dold et al., 2023)”.

Minor correction.

Lines 74–75: The statement that chrysocolla requires only meteoric water to be edited, and if stated, needs a reference.

We modified the text in Introduction section, accordingly, see Line 63-64:
“Therefore, chrysocolla in the copper deposits hosted in the Coastal Cordillera precipitates from meteoric waters (Crane et al., 2001; Palacios et al., 2011; Kahou et al., 2021; Dold et al., 2023).”

Line 77: Edit to specify that alunite was dated in Puntillas, Coastal Cordillera by Sillitoe & McKee (1996).

We modified the text, accordingly, see Line 95-97:
“(2) chrysocolla is the most abundant supergene mineral in the Coastal Cordillera; (3) until now, no other supergene mineral phase that can be dated, such as alunite (e.g. Sillitoe and McKee, 1996) or goethite, has been found in deposits within the Coastal Cordillera”

Line 183: Clarify the text to reflect that atacamite shows replacement textures after chrysocolla, rather than chrysocolla replacing atacamite.

We modified the text to clarify the sentence, see Line 202-203:
“Atacamite, the second most abundant mineral in our samples, shows replacement textures after chrysocolla.” (Figure 5)

Figure 12: Add sample site names to the figure to help the reader interpret spatial relationships.

We modified the figure accordingly and added sample site names. Note that now it is the Figure 13 (see Page 23).

Line 307: Remind the reader that the sample site "Michilla" is not used in the analysis.

We modified this sentence and make clear that the Michilla site is not used in the analysis and further interpretation. Line 344-346:
"The study sites are located on the western side of the Coastal Cordillera (Figs. 1 and 2). The dated samples were taken from abandoned mine sites with an altitude that range from 821 to 2084 m a.s.l. (Table 1) in Marimaca, Caleta El Cobre and Paposo; no results were obtained from Michilla".

Line 345: Note that uplift rates along the Coastal Cordillera vary significantly along strike, and this spatial variability may be relevant to the discussion.

We modified the text to improve the discussion about uplift rates and fog influence, see Line 385-393:
"If coastal fog is the main driver providing moisture to initiate supergene mineralisation, the older ages indicate that the supergene deposits were uplifted above the maximum fog height and therefore supergene mineralisation ceased. Uplift rates along the Coastal Cordillera vary significantly along strike. Reported uplift rates range from ~45 m My^{-1} during the Late Cretaceous to Paleocene (Juez-Larré et al., 2010) to ~600 m My^{-1} during the Pleistocene (Martinod et al., 2016). The obtained ages may therefore be influenced by heterogeneous uplift rates along the Coastal Cordillera, which could have uplifted samples above the zone of fog influence after supergene mineralisation, disconnecting them from any moisture supply capable of sustaining supergene processes. In addition, both fog intensity and fog height may vary through time in response to climatic changes. Consequently, supergene activity along the Coastal Cordillera is likely controlled by two main forcing factors: spatially variable uplift rates along strike and temporal variations in fog intensity and maximum fog height."

Check that all papers cited in the manuscript are included in the reference list.

We checked this and now all publications are correctly cited in the manuscript and are included in the reference list.

We thank Laura Evenstar for the very detailed review of our manuscript and highly appreciate the valuable input. We corrected and modified the manuscript to meet the reviewers' comments and questions.