

# GEOCHRONOLOGY INSIGHTS FOR THE SALOBO DEPOSIT: EVALUATING THE ROLE OF MULTIPLE EVENTS IN A WORLD-CLASS IOCG DEPOSIT

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## ABSTRACT

Multiple superimposed mineralizing events can be important to improve the concentration of valuable elements in ore deposits. The Salobo deposit (Carajás Province, Brazil) exhibits a wide range of rock ages (Mesoarchean to Paleoproterozoic), with potential hydrothermal events at around 2.7, 2.4, 2.1 Ga, and the main mineralizing event at ca. 2.59-2.54 Ga. The first hydrothermal input may have occurred around 2.7 Ga, associated with fluid-induced deformation (shear activation), followed by metamorphism at ca. 2.65 Ga. The major ca. 2.5 Ga mineralizing event generated high-temperature mineral assemblages, resultant from the circulation of magma-derived fluids with minimal non-magmatic contributions. This event possibly occurred through several hydrothermal pulses over ca. 50 Ma or the evolution of a single event, imprecisely defined by the geochronological record. Overprinting events are suggested by low-temperature post-ore alteration, and dated at 2.4 and 2.1 Ga, although these ages may represent isotopic disturbances. This uncertainty reduces the possibility of ore remobilization or additional copper enrichment in the deposit during the Paleoproterozoic.

**KEYWORDS:** Geochronology; Salobo Deposit; Carajás Province.

## INTRODUCTION

The metallogenic evolution of Iron Oxide Copper-Gold (IOCG) deposits is often attributed to multiple superimposed Cu-Au mineralizing events (e.g., del Real et al. 2021), as supported by; (i) the presence of diverse mineralization styles within a deposit (e.g. disseminated and brecciated ore); (ii) the variability in characteristics of fluids involved, inferred from stable isotopes and fluid inclusion studies and; (iii) the geochronological record from various geothermometers. This interpretation is reinforced by studies that highlight the temperature variations in hydrothermal fluids, during different hydrothermal pulses (del Real et al. 2021) or variations in formation depths across successive hydrothermal events (Monteiro et al. 2008). Multiple mineralizing events can remobilize, re-concentrate, and introduce new elements during superimposed events (Skirrow 2021).

The Carajás Mineral Province (N Brazil) is renowned for hosting numerous IOCG (Iron Oxide Copper-Gold) deposits, including the country's largest copper producer, the Salobo copper mine (38 Mt of ore/year @0.6% Cu; ANM 2023). This deposit evolution is attributed to the development of a robust IOCG hydrothermal system, which generated substantial volumes of copper ore around 2.57 Ga (Requia et al. 2003). The primary mineralization event was overprinted by later hydrothermal activity around 2.45 Ga (Melo et al. 2016) and possibly 2.1 Ga (Tassinari et al. 200). Older 2.7 Ga ages are envisaged as the first register of an early hydrothermal system (Tassinari et al. 2003).

Despite the complex geological history, fluid signatures, mineralization and alteration styles observed in Salobo show minimal changes throughout its evolution. Except for the local post-ore alteration (chlorite-, potassium feldspar- and hematite-rich), the hydrothermal alteration is predominantly dominated by high-temperature assemblages (hastingsite-actinolite, almandine-grunerite-magnetite, biotite; Melo et al. 2016), which envelope the massive bornite-chalcocite-magnetite ore. High-temperature fluids (565 °C) of typical magmatic signature ( $\delta^{18}\text{O}_{\text{H}_2\text{O}} = 7.2\text{-}9.7\text{ ‰}$ ), displaying minimal or no mixing tendency with non-magmatic fluids are accounted for the deposit's evolution (Melo et al. 2019). Therefore, the main ore appears to have formed during a single hydrothermal event, with no clear evidence of subsequent remobilization or additional copper enrichment.

In this work, we aim to discuss the geochronological register in the Salobo deposit after a review of geochronological data from the deposit, along with a new age obtained through U-Pb titanite dating. We interpret these data to understand the importance of the multiple registers and underscore the significance of the 2.5 Ga event for the genesis of the Salobo deposit.

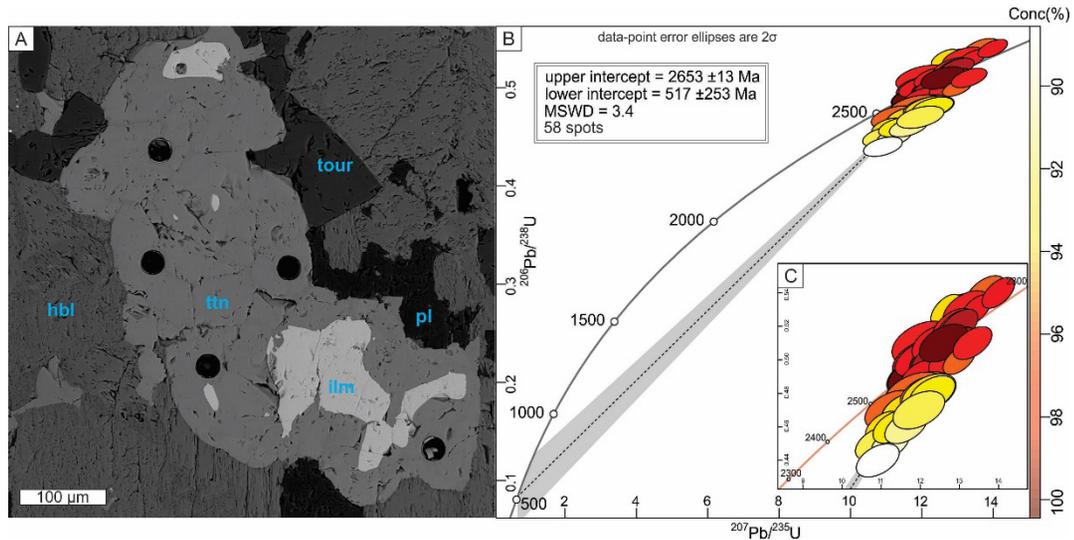
## MATERIALS AND METHODS

This work reports a compilation of the available geochronological data about the rocks at the Salobo Deposit, put together with new data on U-Pb (titanite) dating. In-situ titanite dating was conducted in a polished thin section of an amphibolite sample (SAL177-131). U-Pb analysis were obtained using a 213 nm CETAC laser coupled to a Thermo Scientific Element 2 sector field (SF) ICP-MS, in the Geochronology Laboratory facility of the Federal University of Ouro Preto (UFOP). The analytical procedure followed that described by Aguilar et al. (2017). Uncertainties given for individual analyses (ratios and ages) are at the  $2\sigma$  level.

## RESULTS

### Amphibolite U-Pb titanite age

In the Salobo deposit, amphibolites occur interlayered with schists or as enclaves in granitoids. The studied sample (SAL177-131) has nematoblastic texture, it is dark green, fine- to medium-grained, composed of hornblende (40%), tourmaline (25%), plagioclase (10%), titanite (10%) and, ilmenite (5%), with accessory apatite (2%), and hydrothermal minerals such as sulfides (3%), magnetite (2%), chlorite (2%) and biotite (1%). Titanite occurs as reaction coronas around ilmenite crystals, partially included in hornblende or in the contact between hornblende, plagioclase and tourmaline, showing ilmenite inclusions (Figure 1A). 58 analyzed spots in titanite from this sample yielded a Discordia with an upper intercept at  $2653 \pm 13$  Ma, a lower intercept of  $517 \pm 253$  Ma and a MSWD of 3.4 (Figure 1B, C).



**Figure 1.** (A) Analyzed titanite, showing contacts with ilmenite (inclusions), hornblende, tourmaline and plagioclase. (B) and (C)  $^{206}\text{Pb}/^{238}\text{U}$  vs.  $^{207}\text{Pb}/^{235}\text{U}$  diagrams for titanite analyses (ellipses colored following the concordance rate in the right-side bar)

### Summary of the geochronological data for the Salobo Deposit

The Table 1 summarizes the reported geochronological data and interpretation for rocks at the Salobo deposit.

**Table 1.** Summary of the geochronological data for rocks of the Salobo deposit.

Lithology	Interpretation	Age(Ma)	Method	Reference	
Young Salobo Granite	Paleoproterozoic magmatism	1880 ±80	Rb-Sr	wr	Cordani (1981)
Chloritized gneiss	Hydrothermal overprint	2092 ±120	Rb-Sr	wr	Tassinari et al. (2003)
Magnetite-rich rock	Hydrothermal overprint	2112 ±12	Pb-Pb	mag	Tassinari et al. (2003)
Cu-Au ore	Late ore	2427 ±13	Pb-Pb	ccp	Tassinari et al. (2003)
Cu-Au ore	Late ore	2452 ±14	U-Pb	mz	Melo et al. (2016)
Magnetite-rich rock	Iron-enrichment	2497 ±5	U-Pb	ttn	Machado et al. (1991)
Cu-Au ore	Ore	2535 ±8.4	U-Pb	zr	Melo et al. (2016)
Old Salobo Granite	Magmatism	2547 ±5.3	U-Pb	zr	Melo et al. (2016)
Magnetite-rich rock	Iron-enrichment	2551 ±2	U-Pb	mz	Machado et al. (1991)
Old Salobo Granite	zr reset (hydrothermal)	2554 ±3	U-Pb	zr	Toledo (2022)
Amphibole-rich rock	Iron-enrichment	2555 ±4	U-Pb	zr	Machado et al. (1991)
Cu-Au ore	Ore	2562 ±8	Re-Os	mo	Requia et al. (2003)
Old Salobo Granite	Magmatism	2573 ±2	U-Pb	zr	Machado et al. (1991)
Garnet-amphibole schist	Grt reset (hydrothermal)	2573 ±58	Sm-Nd	grt	Toledo (2022)
Cu-Au ore	Ore	2576 ±8	Re-Os	mo	Requia et al. (2003)
Cu-Au ore	Ore	2579 ±71	Pb-Pb	bn-ccp	Tassinari et al. (2003)
Amphibole-rich rock	Sodic-Calcic alteration	2581 ±5	U-Pb	ttn	Machado et al. (1991)
Tourmaline-rich rock	Sodic-Calcic alteration	2587 ±15	Pb-Pb	tou	Tassinari et al. (2003)
Garnet-amphibole schist	Dynamic metamorphism	2635 ±18	Lu-Hf	grt	Toledo (2022)
Amphibolite	Dynamic metamorphism	2653 ±13	U-Pb	ttn	This work
Igarape Gelado mylonite	Deformation (shear)	2701 ±30	U-Pb	zr	Melo et al. (2016)
Cu-Au ore	First hydrothermal event	2705 ±42	Pb-Pb	cc	Tassinari et al. (2003)
Igarape Gelado Gneiss	Neoproterozoic magmatism	2744 ±4	U-Pb	zr	Toledo (2022)
Igarape Gelado Gneiss	Neoproterozoic magmatism	2731 ±7	U-Pb	zr	Toledo (2022)
Amphibolite	Neoproterozoic magmatism	2761 ±3	U-Pb	zr	Machado et al. (1991)
Igarape Gelado Gneiss	Neoproterozoic magmatism	2763 ±4.4	U-Pb	zr	Melo et al. (2016)
Xingu Complex	Mesoarchean magmatism	2950 ±25	U-Pb	zr	Melo et al. (2016)

## DISCUSSIONS AND CONCLUSIONS

The rocks at the Salobo deposit exhibit a broad range of ages, spanning from the Mesoarchean to the Paleoproterozoic (Table 1). Mesoarchean 2.95 Ga and Neoarchean 2.76-2.73 Ga U-Pb zircon ages represent host rock crystallization (Melo *et al.* 2016; Toledo 2022). The 2.76-2.73 Ga Igarapé Gelado corresponds to the largest magmatic event of the PMC, and the 2.76 Ga amphibolite relates to the Itacaiúnas volcano-sedimentary sequence.

The 2.70 Ga (U-Pb zircon; Melo *et al.* 2016) age of the Igarapé Gelado mylonite results from deformation-induced zircon reset due to the Cinzento Shear Zone activity. This age corresponds to the less precise Pb-Pb age of chalcocite leachates (Tassinari *et al.* 2003) and is broadly identified in the southern region of the CMP (2.68-2.71 Ga; Moreto *et al.* 2015). It potentially represents the first fluid influx in the Salobo deposit, though it may have been obscured by the subsequent ca. 2.5 Ga event.

The 2.65-2.63 Ga ages of titanite (U-Pb) and garnet (Lu-Hf) predate the main mineralization by approximately 90 Ma. According to Toledo (2022), the garnet age represents a metamorphic event reaching approximately 800 °C (Lu-Hf closure temperature; Johnson *et al.* 2018). The U-Pb isotopic system in titanite closes at around 700 °C (Frost *et al.* 2000), thus the contemporary age likely reflects the same event. Furthermore, the petrographic characteristics of titanite, forming coronas around (igneous?) ilmenite, suggest its possible metamorphic origin. This data reinforces the existence of a metamorphic event, still poorly understood in the region.

A series of ages from 2.59-2.54 Ga, obtained from different chronometers, correspond to the main hydrothermal mineralizing event. Molybdenite ages (2.57-2.56 Ga) are considered the best representatives of this event due to the undoubtable correlation of this sulfide with the Cu ore (Requia *et al.* 2003). Moreover, the Re-Os chronometer in molybdenite is highly robust, as it is less affected by factors such as inheritance, incorporation of common Os, and radiogenic Os loss during recrystallization (Stein *et al.* 2002). Thus, ages of other hydrothermal minerals, (2.58 Ga Pb-Pb tourmaline and bornite-chalcocite; Tassinari *et al.* 2003 and 2.55 Ga U-Pb monazite; Machado *et al.* 1991), are confidently related to this event.

Toledo (2022) interprets the 2.57-2.55 Ga U-Pb zircon ages from the Old Salobo granite reflect isotopic resetting due to IOCG fluids. The author also discusses that the 2.57 Ga Sm-Nd register in garnet represents isotopic disturbance caused by the high temperature fluids of the coeval hydrothermal event, since it formed much earlier at 2.65 Ga (Lu-Hf age). Hydrothermal fluids at 565 to 540 °C (Melo *et al.* 2019; Toledo 2022) possibly enhanced diffusion rates in garnet, facilitating isotopic re-equilibration (Dodson 1973), in conditions under the closure temperature of the Sm-Nd isotopic system (700 °C; Johnson *et al.* 2018). The 2.58 Ga age for titanite may also result from isotopic reset and Pb loss.

The Salobo deposit exhibits compelling evidence of a hydrothermal event around 2.59-2.54 Ga. However, the timespan covered by the records (approximately 50 Ma) is not compatible with the evolution of hydrothermal systems, which typically span up to 2 Ma (e.g., Chiaradia *et al.* 2012). Multiple overprinted pulses of hydrothermal events may have occurred. Alternatively, the imprecision resulting from the old age of the hydrothermal system could contribute to the record of multiple ages that, in fact, represent the evolution of a single system.

A few 2.49-2.43 Ga ages are related to monazite (U-Pb), titanite (U-Pb), and chalcopyrite (Pb-Pb) dating, potentially associated with subsequent events forming chlorite-rich Fe-hydrated alteration zones. However, monazite ages may reflect isotopic reset due to its efficient dissolution-precipitation under hydrothermal conditions (Teufel and Heinrich 1997). Chalcopyrite and titanite ages could indicate significant Pb loss during hydrothermal system cooling. Likewise, the 2.1 Ga Paleoproterozoic ages obtained from magnetite (Pb-Pb) and whole rock (Rb-Sr) may represent a younger hydrothermal overprint or reflect Pb loss or disturbance of the Rb-Sr isotopic system, triggered by the 1.88 Ga anorogenic magmatism event. Therefore, it is challenging to determine whether the ca. 2.4 Ga or ca. 2.1 Ga ages represent superimposed events or isotopic disturbances, what reduces the likelihood of ore remobilization or additional copper enrichment during the Paleoproterozoic.

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