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How to create the highest manganese ore grade in the world?

A geodynamic story in the Atlas of Morocco



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Introduction

The Imini mining district hosts the **largest Mn resources of North Africa** due to two laterally extensive ore bodies (~25-30 km) of **nearly pure pyrolusite** (MnO₂). A third medium-grade coronadite-rich (K,Ba,PbMn₈O₁₆) Mn ore occurs discontinuously over a wider area of ~100 km. The two ore types are hosted in a poorly deformed 10-15m-thick Cenomanian-Turonian dolostone unit located in the southern foreland of the High Atlas of Morocco. Until now, the **source of the metals and the timing** of ore deposition remains unclear for this unconventional karst-hosted deposit.

Objectives and methods

We examine the **Pb isotope** composition of the Mn ores and the most representative country rocks to track down potential sources of the metals. We also study the age of the K-bearing Mn oxides present in the Mn ore by ⁴⁰Ar/³⁹Ar. By combining these two methods we are able to produce a consistent model of the ore deposition.

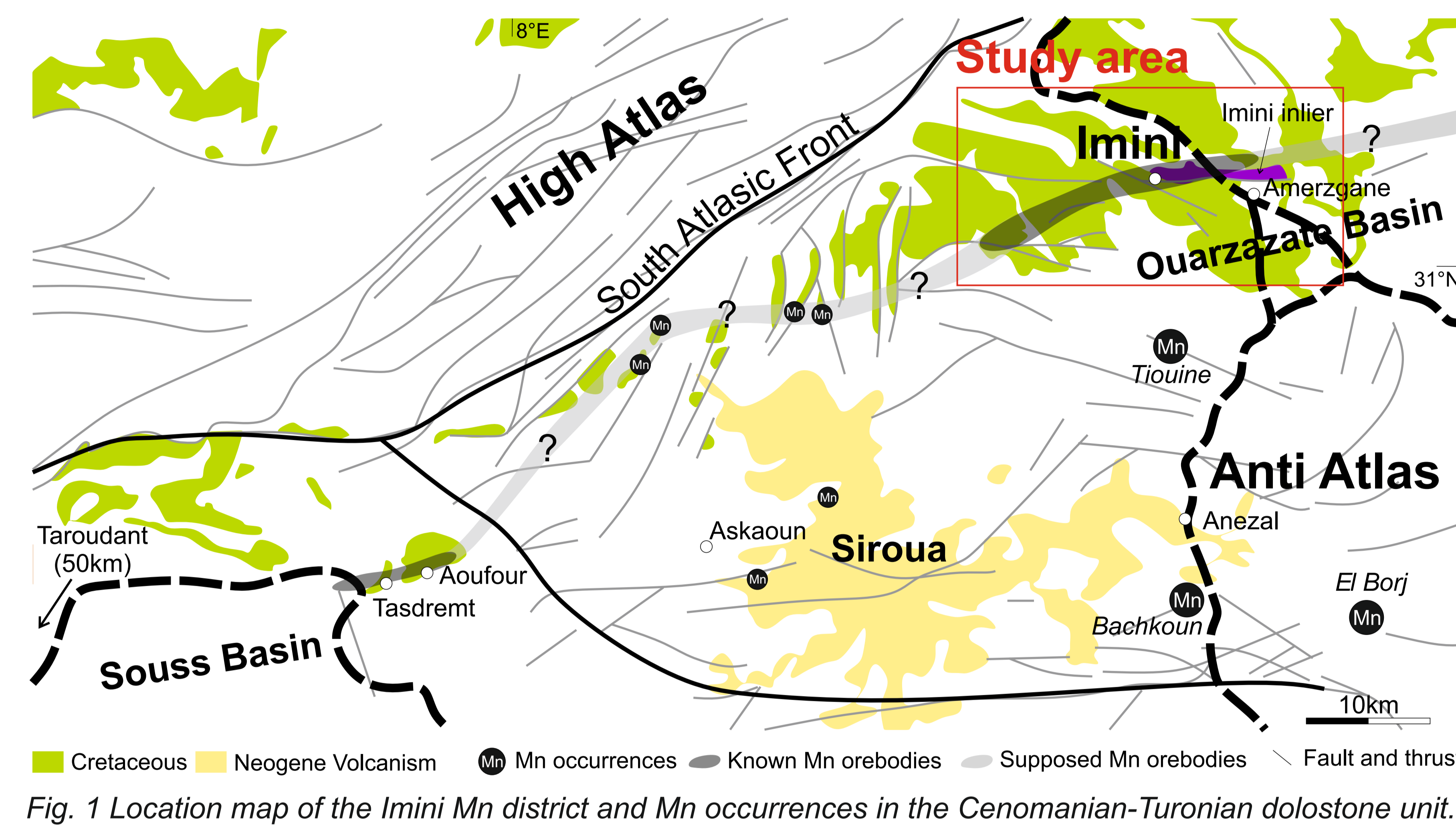


Fig. 1 Location map of the Imini Mn district and Mn occurrences in the Cenomanian-Turonian dolostone unit.



Fig. 2 Field photograph of the Lantenois mine showing the high-grade pyrolusite-rich ore (C2) and the medium-grade coronadite-rich Mn ore (C3)

Key interpretations

- **Atlas tectonics** is the first-order control of the Mn mineralization.
- Periods with regionally high elevations modified the climate to wetter conditions that brought rather **continuous supplies of meteoric water** to feed temporary aquifers.
- **Relief building created the required hydraulic head** to sustain (1) fluid-rock interaction between O₂-poor acidic fluids and the Triassic series, (2) migration of the metal-rich fluid and (3) overpressure fluid in the Imini depositional site.
- The disappearance of Triassic series in front of the Imini anticline forced these low-temperature (<100°C) fluids to **mix with oxygenated ground and alkaline waters** resident in the karst system and precipitate Mn oxides.
- The N70°-oriented **Atlas tectonic structure controls the orientation** of the Mn deposits.
- Post-Cretaceous uplifts generated **additional supplies and/or in-situ remobilizations** of the primary late Cretaceous medium-grade ore to form the high-grade pyrolusite-rich ore in Imini.

Results

The new Pb isotopic ratios show that **Triassic series (basalts and Fe-rich sandstones) are likely the source** of the metals. The ⁴⁰Ar/³⁹Ar dating of these K-Mn oxides shows that the Mn-rich ore bodies formed during at least **three periods**:

- late Cretaceous to late Paleocene (>58 Ma)
- late Eocene (c. 36.3 Ma)
- early Burdigalian to early Serravalian (c. 19–20 Ma and c. 13 Ma)

These periods **coincide with three known Atlas geodynamic deformation** events during late Cretaceous, late Eocene and the Early(?)–Middle Miocene.



Fig. 3 Pb isotope composition of the Imini Mn oxide ores and different country rocks.

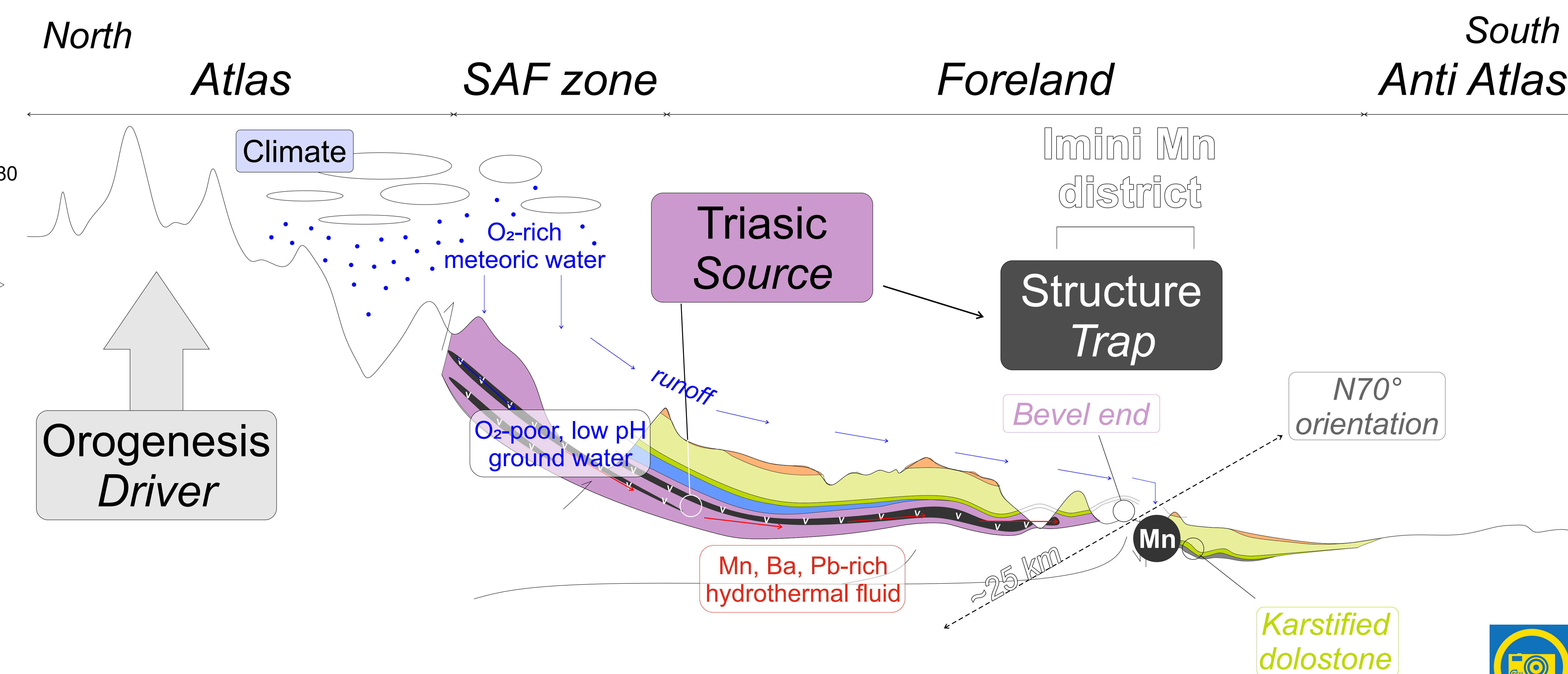


Fig. 5 Formation model of the high-grade Imini Mn ore deposits due to multiple orogenic phases of the Atlas.

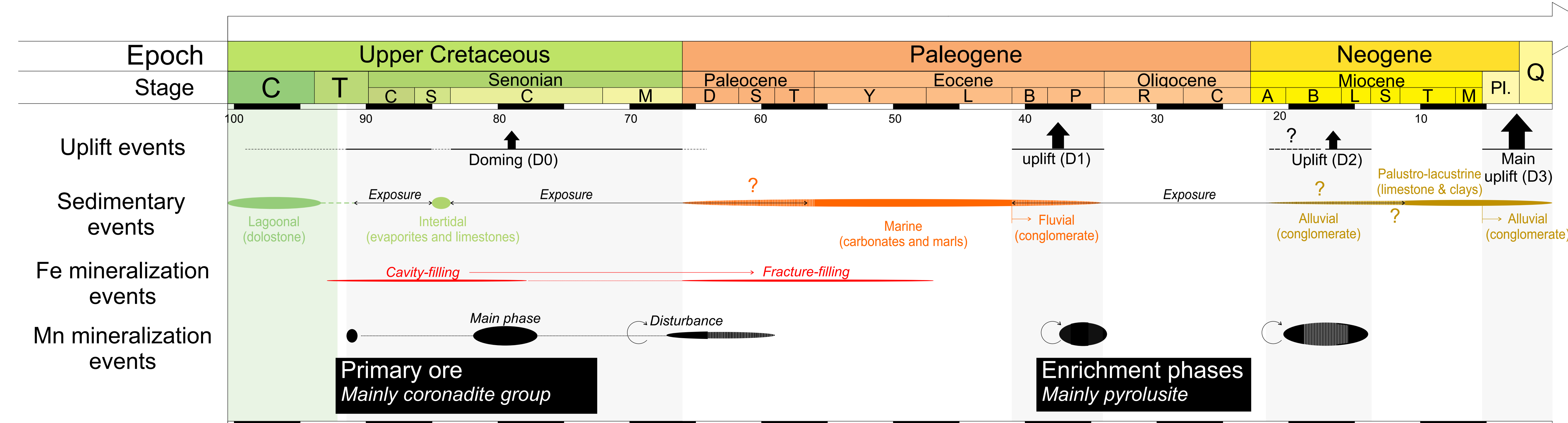


Fig. 4 Chronology chart of Mn deposition based on ⁴⁰Ar/³⁹Ar dating of coronadite group minerals and other events of the area. See the best fit between uplift events and K-Mn oxide ages.

