Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.25917

Integrating calcite U-Pb and hematite (U-Th)/He dating with clumped isotope analysis to unravel orogenic evolution and fluid circulation in the Western Alps

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Alpine orogenic models have evolved significantly over time. Initially framed by the geosynclinal theory in the 1910s, later refined into a purely collisional framework with the advent of plate tectonics. In the 1990s, extensional seismicity recorded in the Internal Western Alps was interpreted as gravitational collapse and later as isostatic rebound, or mantle-driven processes. The recent development of new methods of dating and geochemical characterisation is bringing new constraints to these models.

Our data set made of 33 U-Pb calcite dates coupled to 59 (U-Th)/He hematite dates, reveal a synchronous yet contrasting stress regime: compressional deformation in the subalpine foreland (13.3 to <0.8 Ma) and extensional deformation in the Western alpine wedge (15.4 to 2.1 Ma). This suggests a syn-orogenic stage linked to the exhumation of the External Crystalline Massifs. Rather than behaving as a homogeneous block subjected to a uniform stress field, the orogen appears to be composed of smaller, interacting tectonic blocks, with deformation localized along pre-existing lithospheric structures. This highlights the role of these ancient structures in accommodating differential stress distribution and shaping the evolution of the mountain belt.

Fluid circulation associated with fault activity was investigated using clumped isotopes (Δ_{47}) and stable isotopes ($\delta^{18}O$, $\delta^{13}C$). Results indicate both meteoric and hydrothermal fluid signatures, with temperatures ranging from 54–149°C in the subalpine foreland and 36–133°C in the Western alpine wedge. These findings highlight deep-rooted fault systems with connection to surface processes. The transition from deep to surface fluid mobilization may result from either fault propagation to the surface or regional exhumation bringing fault systems into the surface fluid influence zone (~2-3 km depth).

The interplay between deformation timing and fluid circulation provides critical insights not only into orogenic evolution, but also into broader geodynamic processes. These findings have direct implications for orogenic gold mineralization, paleoenvironmental reconstructions, and seismic hazard assessments.