Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.30014

Insights on deformation stages during fluid-filled fissure evolution using fluid inclusion analysis and monazite geochronolgy on the example of the Grimsel Pass in the Central Alps, Switzerland

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Fluid-filled fissures and clefts serve as valuable archives of tectonic evolution, particularly in exhuming orogenic belts where low-temperature deformation records are often elusive. Our research integrates fluid and solid inclusion analysis, Ti-in-quartz thermometry, solute thermometry, and monazite-(Ce) Th-Pb dating to link quartz growth with episodic faulting events in the Grimsel Pass region, Swiss Central Alps. Our investigation refines the chronology of deformation by correlating mineral growth with changing fault kinematics and fluid conditions.

The results reveal an early phase of inverse faulting that formed horizontal fissures under greenschist-facies conditions of 450°C/440 MPa . This was followed by a transition to dextral strike-slip faulting, which caused the formation of vertical fissures. Detailed study of quartz fluid inclusions identified up to six distinct populations, with four populations preserved in the later, vertical fissures. The significant regional stress field shift from inverse faulting to strike-slip around ~12–11 Ma triggered major fluid migration, leading to the alteration of mineral assemblages and initiated monazite-(Ce) growth. A subsequent CO_2-enriched fluid influx during renewed dextral faulting facilitated further mineralization, while meteoric water infiltrated during late-stage evolution.

By combining quartz growth zoning, fluid inclusion chemistry, and monazite geochronology, this study demonstrates the utility of cleft mineral analysis in reconstructing complex deformation histories. The refined P–T–t evolution underscores the significance of fluid-filled fissures as long-term geodynamic recorders. These insights not only enhance our understanding of the interplay between tectonics and fluid flow during orogenic exhumation but also have broader implications for interpreting fluid–rock interactions in active mountain belts.