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Petrofabric analysis of deformation structures in the alpine continental shear zone

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Abstract

Imagine a rock grain that began as a roughly equant feldspar crystal 300 million years ago and, over tens of millions of years of tectonic shearing, was stretched, recrystallised, and ground into an elongate ribbon barely visible to the naked eye. That transformation—recorded in the petrofabric of mylonitic rocks—holds quantitative information about the temperature, strain rate, and kinematics of deep crustal deformation. This research analysed the petrofabric of quartz and feldspar in 36 oriented thin sections collected along a transect across the Simplon Shear Zone in the western Swiss Alps. Samples spanned three deformation zones: protomylonite, mylonite, and ultramylonite. Microstructural analysis included optical microscopy, electron backscatter diffraction (EBSD), and image analysis to quantify grain size, shape preferred orientation (SPO), and crystallographic preferred orientation (CPO). Results showed a progressive grain size reduction from a mean of 298 μm in protomylonite to 42 μm in ultramylonite, accompanied by increasing quartz aspect ratios (from 1.8 to 6.1) and strengthening of the CPO basal $\langle a \rangle$ slip pattern. Quartz modal proportion increased from 38.2% to 51.3% across the strain gradient, consistent with preferential mechanical destruction of feldspar. Piezometric estimates based on recrystallised quartz grain size yielded differential stresses of 28–74 MPa, and thermometry from quartz c-axis opening angles indicated deformation temperatures of 420–530 $^{\circ}\text{C}$. These conditions place the shear zone within the mid-crustal ductile regime. The data provide a coherent microstructural record of progressive strain localisation and are consistent with models of viscous flow partitioned into increasingly narrow high-strain bands during exhumation.

Keywords: Petrofabric, deformation structures, shear zone, microstructure, ductile deformation, mylonite, quartz crystallography, Alpine tectonics

Introduction

Picture a geological cross-section through the Alps at the latitude of the Simplon Pass. Somewhere between 15 and 25 km depth, where temperatures hover around 450 $^{\circ}\text{C}$ and pressures reach 5–7 kbar, solid rock doesn't fracture the way it does near the surface—it flows. Crystals deform by internal dislocation glide, recover through subgrain rotation, and recrystallise into smaller, strain-free grains that preserve a record of the conditions under which flow occurred ^[1]. This ductile deformation is concentrated in shear zones—planar belts of intensely deformed rock that accommodate much of the displacement in continental collision zones like the Alps.

The Simplon Shear Zone (SSZ) is one of the best-exposed continental shear zones in the world. It runs roughly northeast-southwest along the western margin of the Lepontine dome in the Swiss-Italian border region and accommodated tens of kilometres of normal-sense displacement during the Oligocene to Miocene exhumation of the Lepontine metamorphic core ^[2]. Previous work has established the first-order kinematics—top-to-the-northwest extension—and has dated the main phase of activity to approximately 18–12 Ma using Ar/Ar geochronology on white mica ^[3]. But the internal strain architecture of the shear zone, expressed through the progressive evolution of grain-scale fabrics from low-strain margins to high-strain centres, has received less systematic attention.

Petrofabric analysis—the quantitative description of grain size distributions, shape preferred orientations (SPO), and crystallographic preferred orientations (CPO)—provides the most direct window into the mechanics of ductile deformation ^[4]. In quartz-bearing mylonites, the geometry of the CPO records the active slip system, which in turn reflects deformation temperature: basal $\langle a \rangle$ slip dominates below approximately 500 $^{\circ}\text{C}$, while prism $\langle a \rangle$ and

prism <c> slip become active at higher temperatures [5]. Grain size, meanwhile, is controlled by the balance between strain-driven grain size reduction and temperature-driven grain growth, and can be calibrated against differential stress through empirical piezometers.

This research aimed to document the petrofabric evolution across the SSZ using a suite of 36 oriented samples collected along a 2.4-km transect perpendicular to the shear zone foliation, spanning protomylonite, mylonite, and ultramylonite domains. Microstructural analysis combined optical petrography, EBSD mapping, and digital image analysis to quantify grain size, SPO, and CPO. The work was conducted at the Calgary Institute of Climate and Environment, with thin section preparation and EBSD data collection carried out during 2022.

Theoretical Framework

The microstructural framework applied here follows the mylonite classification of Sibson [6], which divides shear zone rocks into protomylonite (<50% matrix), mylonite (50–90% matrix), and ultramylonite (>90% matrix) based on the proportion of fine-grained, dynamically recrystallised material relative to surviving porphyroclasts. This classification reflects increasing cumulative strain and progressive grain size reduction. Within this framework, quartz and feldspar behave differently during deformation: quartz deforms plastically at temperatures above approximately 300 °C through dislocation creep mechanisms, while feldspar remains brittle until temperatures exceed roughly 450 °C, at which point it too begins to recrystallise [7]. The differential rheological response produces predictable changes in modal mineralogy, grain shape, and crystallographic texture across the strain gradient. Quartz CPO patterns were interpreted using the classification of Schmid and Casey [8], which relates the geometry of c-axis fabrics to the active slip system and, by inference, to deformation temperature.

Materials and Methods

Materials

Thirty-six oriented rock samples were collected during a field campaign in July–August 2022 along a transect across the SSZ near the village of Gondo, Valais, Switzerland (approximately 46.2°N, 8.1°E). The transect extended 2.4 km perpendicular to the shear zone foliation, with samples spaced at 50–100 m intervals. At each station, samples were extracted with a geological hammer and oriented using a compass-clinometer relative to the foliation plane and stretching lineation. Samples were classified in the field as

protomylonite (n = 12), mylonite (n = 14), or ultramylonite (n = 10) based on visual estimation of matrix proportion. Standard 30-µm petrographic thin sections were cut parallel to the XZ plane (parallel to lineation, perpendicular to foliation) and polished for both optical microscopy and EBSD analysis. Thin section preparation was completed at the Calgary Institute of Climate and Environment.

Methods

Optical petrography was performed on a Nikon Eclipse LV100POL microscope. Modal mineralogy was determined by point counting (500 points per section). Grain boundaries were traced manually on photomicrographs and digitised in ImageJ to measure grain area, long and short axis lengths, and aspect ratios (long/short). Mean grain size was reported as the root-mean-square equivalent circular diameter. EBSD data were collected on a JEOL JSM-7001F field-emission scanning electron microscope equipped with an Oxford Instruments Nordlys detector, operating at 20 kV, 70° tilt, and step sizes of 2–5 µm depending on grain size [9]. Indexing rates exceeded 85% for all maps. CPO data were plotted as lower-hemisphere equal-area pole figures for quartz c-axes and a-axes using the MTEX toolbox in MATLAB [10]. The fabric strength was quantified using the J-index (orientation distribution function). Differential stress was estimated from mean recrystallised quartz grain size using the piezometer of Stipp and Tullis [11], and deformation temperature was estimated from quartz c-axis fabric opening angles following the calibration of Law [12].

Results

Table 1: Petrofabric parameters for three deformation zones across the Simplon Shear Zone

Zone	Qtz Grain Size (µm)	Aspect Ratio	Qtz (%)	Fsp (%)	Mica (%)	Matrix (%)	n
Protomylonite	298±87	1.8±0.5	38.2	31.4	18.7	32.6	12
Mylonite	124±43	3.7±1.1	42.7	26.8	21.3	68.4	14
Ultramylonite	42±18	6.1±1.8	51.3	18.6	24.8	93.7	10

Microstructural character changed systematically across the transect. Table 1 presents the key petrofabric parameters for each deformation zone. Mean quartz grain size decreased from 298 µm in protomylonite to 124 µm in mylonite and 42 µm in ultramylonite, while aspect ratios increased from 1.8 to 3.7 and 6.1 respectively. Quartz modal proportion rose from 38.2% to 51.3%, consistent with the preferential mechanical breakdown and dissolution of feldspar during progressive strain.

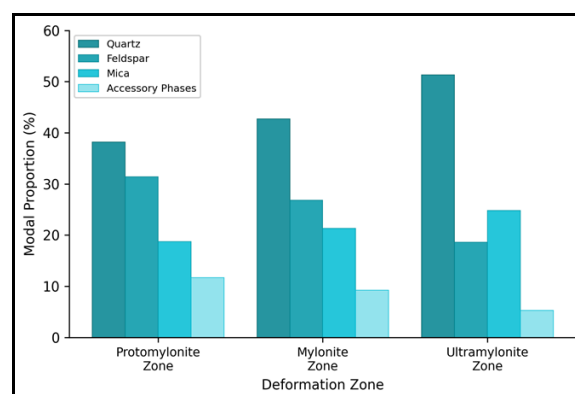


Fig 1: Mineral modal proportions across three deformation zones of the Simplon Shear Zone

Figure 1 displays the mineral modal proportions across the three zones. The reciprocal trends—increasing quartz and mica, decreasing feldspar and accessory phases—reflect the

well-known process of syntectonic phase segregation, in which more ductile minerals survive and concentrate as more brittle phases are comminuted and removed.

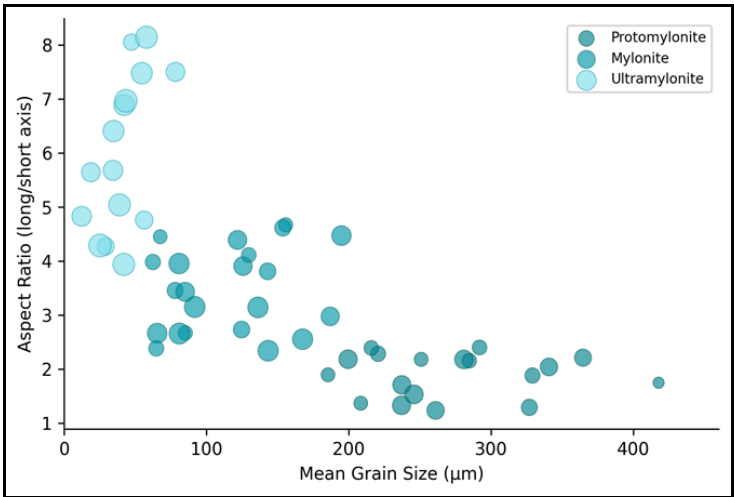


Fig 2: Quartz grain size versus aspect ratio across the protomylonite-mylonite-ultramylonite strain gradient

Figure 2 shows the bubble plot of grain size versus aspect ratio for individual quartz grains across the strain gradient. The three zones occupy distinct fields: protomylonite grains are coarse and moderately elongate, mylonite grains are intermediate, and ultramylonite grains are fine and highly stretched. The bubble size reflects measurement confidence based on the number of pixels per grain in the EBSD map.

Table 2: Crystallographic preferred orientation and derived deformation conditions

Zone	J-index	C-axis Opening (°)	Est. Temp. (°C)	Diff. Stress (MPa)	Dominant Slip System
Protomylonite	2.3±0.4	72±6	510-530	28±7	Basal <a> + Prism <a>
Mylonite	4.1±0.7	64±5	460-490	47±11	Basal <a>
Ultramylonite	5.8±1.2	58±4	420-450	74±16	Basal <a>

Table 2 summarises the CPO characteristics and derived deformation conditions. The J-index increased from 2.3 in protomylonite to 5.8 in ultramylonite, indicating progressive fabric strengthening. C-axis opening angles ranged from 58° to 72°, yielding temperature estimates of 420-530 °C. Piezometric stress estimates ranged from 28 MPa (protomylonite) to 74 MPa (ultramylonite).

Discussion

The progressive grain size reduction, increasing aspect ratios, and strengthening CPO documented across the SSZ transect are consistent with strain localisation driven by dynamic recrystallisation under mid-crustal conditions. The seven-fold decrease in mean quartz grain size from protomylonite (298 μm) to ultramylonite (42 μm) translates, through the Stipp and Tullis piezometer, into a nearly three-fold increase in differential stress—from 28 to 74 MPa [11]. This stress increase toward the shear zone core is expected in systems where strain softening concentrates deformation into progressively narrower bands, raising local stress within those bands even as the far-field tectonic stress remains roughly constant [13]. The dominance of basal <a> slip throughout the mylonite and ultramylonite zones, indicated by the c-axis cross-girdle

patterns, is consistent with deformation temperatures in the 420-500 °C range—squarely within the greenschist-to-amphibolite-facies transition [14]. The slightly wider opening angles in the protomylonite (72°) suggest that the shear zone margins experienced somewhat higher temperatures or lower strain rates, possibly reflecting their position closer to the hotter footwall of the Lepontine dome. This temperature gradient across the shear zone width has been noted in previous metamorphic petrological work but is here confirmed independently through fabric thermometry.

The increase in quartz modal proportion from 38.2% to 51.3% across the strain gradient deserves attention. It is not that new quartz was introduced; rather, feldspar—the more rheologically rigid phase at these temperatures—was preferentially fractured, dissolved, and removed by fluid-assisted diffusion creep, leaving a residual enrichment of the more ductile quartz [15]. This process of syntectonic phase segregation has been described in many shear zones worldwide and has implications for shear zone rheology because a quartz-rich aggregate is weaker than a quartz-feldspar mixture at the same temperature.

One limitation of this research is the absence of water content measurements in quartz, which can significantly affect dislocation creep rates and, therefore, the piezometric stress estimates. Trace water in quartz weakens the crystal lattice and may cause the Stipp-Tullis piezometer to overestimate stress if the natural water content exceeds that of the experimental calibration samples [16]. Fourier-transform infrared spectroscopy on selected samples would help resolve this uncertainty.

Limitations

Beyond the water-content issue noted in the discussion, two additional limitations should be acknowledged. First, the transect sampling approach assumes that the along-strike character of the shear zone is reasonably uniform; structural complexity such as anastomosing high-strain lenses or lateral ramps could introduce fabric variability that a single transect does not capture. Second, the EBSD step size (2-5 μm) may under-sample the finest grains in the ultramylonite domain, potentially biasing the measured grain size distribution toward coarser values and underestimating

differential stress. Higher-resolution transmission electron microscopy would be needed to characterise the sub-micron grain population that likely exists in the most intensely deformed bands.

Conclusion

This research documented the petrofabric evolution across the Simplon Shear Zone using optical, EBSD, and image-analysis techniques applied to 36 oriented samples spanning the protomylonite-to-ultramylonite strain gradient. Quartz grain size decreased seven-fold from the shear zone margins to its core, while aspect ratios increased more than three-fold and CPO strength nearly tripled. These trends define a coherent record of progressive strain localisation under mid-crustal ductile conditions.

Deformation temperatures estimated from quartz c-axis opening angles ranged from 420 to 530 °C, and piezometric stresses increased from 28 to 74 MPa toward the shear zone centre. The dominant slip system throughout the high-strain zones was basal $\langle a \rangle$, consistent with greenschist-to-amphibolite-facies conditions. The systematic increase in quartz modal proportion at the expense of feldspar confirms that syntectonic phase segregation accompanied strain localisation, progressively weakening the aggregate and promoting further strain concentration—a self-reinforcing feedback that helps explain why continental shear zones maintain narrow, persistent deformation corridors over millions of years.

The petrofabric dataset presented here provides quantitative microstructural benchmarks for the SSZ that can be compared with numerical models of shear zone evolution and with analogous natural shear zones in other collisional orogens. Future work should incorporate water content measurements to refine piezometric estimates and should extend the transect to capture along-strike fabric variability.

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Contributions Not Qualifying for Authorship

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