Crustal Deformation Processes Studied by Microprobe Quantification of Minerals

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INTRODUCTION
Shear zones such as the San Andreas fault in California or the Great Glen fault in Scotland are outstanding examples of concentrated deformation caused by the displacement of two adjacent lithological blocks in the Earth’s crust. If imposed strain rates are mainly accommodated by ductile processes, shear zones are characterised by the development of mylonites from unaltered wall rocks over scales of centimetres to several hundred metres [1].

Due to their often very compact size, ductile shear zones offer an excellent possibility to study metamorphic evolution as well as mechanical and chemical changes along a predefined transect of increasing deformation. Recent investigations of such crustal deformation zones dealt mainly with questions concerning element mobility and related volume changes during shearing and alteration processes [2-7]. Based upon previous publications [8,9], ductile deformation may occur in the following three ways (Figure 1): 1. In ductile shear zones marked by simple shear and the lack of metamorphic fluids, mass transfer and volume change during deformation may be regarded as almost negligible (isovolumetric shear zones). 2. If plane strain is combined with transpression and affected rocks are infiltrated by high amounts of metamorphic fluids, mylonitization is accompanied by mass depletion and volume loss.

In this article, an alternative concept for the determination of possible volume changes between mylonite and wall rock of a ductile shear zone is introduced. In contrast to the hypothesis of immobile elements and all its related uncertainties, the new technique allows a reliable calculation of volume factors and subsequent mass balancing by the quantification of the accessory mineral zircon in samples of the wall rock and the mylonite, using backscattered electron imaging (BSEI) and wavelength-dispersive X-ray spectroscopy (WDS). The method was applied to a medium-grade ductile shear zone located in the western part of the Tauern Window (Eastern Alps, Austria) [9,12].

MATERIALS AND METHODS
Since the shear zone used for this study is characterized by plain strain combined with extensive transpression and, as a consequence, by a remarkable volume loss, the basic concept standing behind the volume (mass) balancing method introduced above is described for the case of a volume-loss shear zone (Figure 2). Assuming accessory zircon as an immobile and highly resistant mineral phase during metamorphic processes, the number of zircon crystals per unit area in shear zone (Nsz) and wall rock (Nwr) negatively correlates with a down reaction and quantification of the fluid flow during deformation.

Figure 1: The three types of volume change in ductile shear zones. 1. Subsimple convergent shear zone (volume loss). 2. Subsimple divergent shear zone (volume gain). 3. Simple shear zone (isovolumetric deformation).
possible volume change between deformed and undeformed rock, i.e. a 30% volume reduction of the mylonite with respect to the wall rock is expressed by a 30% increase in zircon crystals per volume unit within the ductile shear zone ($N_{w} = 0.7 N_{w}$). In the case of volume-gain shear zones, the opposite scenario concerning the crystal number per volume unit in mylonite and wall rock can be observed ($N_{w} > N_{w}$). Following simple stereological considerations, the number of zircon crystals per volume unit can be substituted by the number of zircon sections per square unit, a parameter which may be rather easily determined by electron probe microanalysis (EPMA) using BSE mode. As a basic requirement for a successful application of the two-dimensional analysis, rock deformation in x and y directions has to be regarded as nearly isometric, with changes of the number of crystal sections in the y plane taking place in a similar fashion as in the x-z plane (Figures 1 and 2).

For the microprobe work, polished thin sections (35 × 20 mm), oriented in the manner illustrated in Figure 2B, were produced from both the wall rock and the mylonite. The thin sections were examined using the BSEI mode in a JEOL JXA 8600 microprobe (Figure 3A) with the following settings: acceleration voltage 15 kV, beam current 40 nA, beam diameter 1 μm. In addition to the optical mineral determination, wavelength-dispersive X-ray spectroscopy (WDS) suitable to detect the Zr content in suspicious minerals was applied (Figure 3A). X-rays of Zr were measured by using a thallium acid phthalate (TAP) crystal, which following Rowland circle geometry was positioned a distance of 65.99 mm from the sample surface. Recording of zircon crystal sections was carried out along a predefined set of imaginary lines (Figure 3B), whereby all zircon crystal sections cutting the lines were counted. For counting as effectively as possible, an overall magnification of 400 × was found useful. At this magnification, from each thin section 22 lines, 30 mm long and 0.9 mm apart, were scanned, covering a standardized area of 19.8 × 30 mm.

RESULTS AND DISCUSSION

The quantification method illustrated in Figure 2B was applied to a small-scale shear zone located in the western part of the Tauern Window of the Eastern Alps in Austria (Figure 4A). Within this medium-grade metamorphic deformation zone a metatonalitic wall rock mainly composed of plagioclase, amphibole, biotite, and quartz was transformed into a garnet-chlorite-biotite schist.

Strain analysis provided a significant flattening (oblate deformation) of the shear zone with respect to the wall rock (Figure 2A), being a typical feature of volume-loss deformation. SEM analysis of zircon crystals from wall rock and mylonite underlined the high resistance of this accessory mineral phase to medium-grade deformation (4-5 kilobars, 500-550°C), with metamorphic influence being limited to crystal corrosion and a negligible extent of crystal fracture (Fig 4B). BSEI and WDS were carried out on five polished thin sections of the mylonite and wall rock, respectively, and the results of the counting procedures were subject to a statistical treatment (Table 1). Zircon crystal sections such as those exhibited in Figure 4C were easily recognisable on the monitor due to their bright flashing and internal zoning structure. As shown in Table 1, in the wall rock 0.58 crystal sections per mm² were counted, whereas in the mylonite 0.89 crystal sections per mm² could be determined by the quantification procedure. The related volume factor $f_{V}$ was 0.652, indicating a volume loss between wall rock and mylonite of 34.8% [11]. These data corresponded very well with the results of previous investigations on the same shear zone [12], where geochemical volume and mass-balancing according to Grant’s approach was performed, thereby also suggesting a volume reduction between wall rock and shear zone of about one third.
Based on the volume factor derived from BSEI and WDS, mass balancing of major elements was carried out to show the chemical effects of ductile shearing (Table 1). According to the calculations, the elements Si, Ti, Al, Na, and P were subject to a remarkable partial depletion during deformation, which ranged from 9.5% (P) to 84.4% (Na). The remaining major elements, on the other side, increased their amounts in the shear zone, with Fe and Mg showing the highest growth in concentration (Table 1).

The element mobility in the shear zone clearly reflects the mineralogical transition from a high-Si granitoid to a mafic schist with respective predominance of mineral phases rich in Fe, Mg, Mn, K, and H₂O. A similar alteration was outlined by Selverstone et al. [3] for a shear zone being situated in the same tectonometamorphic unit as the deformation zone described here. The authors calculated a volume loss of up to 60% with extensive major element depletion out of the deformation zone due to fluid channelling processes. However, the important role of metamorphic fluids for the long-range transport of elements has to be also assumed for the exemplary case presented here. In future, the quantification technique will be applied to other low- to medium-grade metamorphic shear zones in the Eastern Alps and the Bohemian Massif.

**CONCLUSIONS**

From the results presented here it can be concluded that the volume-balancing technique based on the BSEI/WDS quantification of zircon crystal sections on polished thin slabs provides an alternative tool for the comprehensive description of crustal deformation processes. At the current stage of this research, however, the introduced method is limited to low- to medium-grade metamorphic ductile shear zones, being characterized by high stability of accessory zircon. If zircon crystals are subject to extensive fracture (e.g. during brittle deformation), significant dissolution (e.g. during high-grade metamorphic deformation), or both, the method will not provide appropriate results without any further mineralogical and chemical investigations resulting in respective correction factors. The determination of such stereological correction factors will be the main objective of future efforts.

**REFERENCES**


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