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Zircon - A possible indicator of mass transfer in deformation zones: A solution for the Roffna gneiss controversy (Suretta nappe, Switzerland)

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ABSTRACT

This paper proposes a simple volume (mass) balancing technique as a means to assess the volume loss and tectonic flattening of mylonitic shear zones. The method involves counting the number of zircon crystals in oriented polished thin sections, analyzed subsequently in the electron microprobe, using the BSEI mode, and a spectrometer setup for detection of the element Zr. Here we present an application to the Roffna gneiss (Eastern Switzerland), a porphyritic granite of Permian origin, which has been metamorphosed and transformed into a phengitic schist under low-grade metamorphic conditions. Mass balances for this material have produced controversial interpretations, in that a first analysis of chemical data of wall rock and mylonite suggested an isochoric mylonitic transition event, while a dramatic volume loss of some 50% in the course this process was inferred after a re-evaluation of the same data. Electron-microscopy of zircon crystals that were retrieved from rocks which had undergone different degrees of deformation revealed only minor alterations and mechanical damage of single grains. This stability of zircon justified the use of single crystals, and in consequence of the element Zr, as passive markers in determining volume (mass) changes during deformation. Results obtained by this method allow us to confirm that the deformation of the Roffna gneiss involved a volume loss of 29 ± 6%, accompanied by chemical alterations. Deformation-induced mobility changes of various elements lead to small gains in Mg and Cr but significant losses Si, Al, Na, Ca, and Sr during the metamorphic event. All other elements, including the REE, underwent no substantial long-range transport.

1. Introduction

1.1. The role of volume change during deformation - general aspects

The role of volume loss and tectonic flattening of mylonitic shear zones in granitoids remains a subject of controversy in numerous studies of tectonized granites (e.g. Selverstone et al., 1991; Ring, 1999). Mass balancing of mylonitic shear zones has important implications not only for determining bulk strain but also for estimating displacement across these zones and, most important regarding our study, for unraveling the role of mass transfer during deformation. If exclusively based on whole-rock chemical analyses, mass balancing may lead to conflicting interpretations of even a single set of geochemical data, a problem that gave rise, for example, to the following controversy: Vocke et al. (1987) presented extensive geochemical data of the variably deformed Roffna gneiss. Based on a graphical evaluation of the data, the mylonitic deformation was interpreted as isovolumetric. Moreover, it was assumed that large fractions of certain trace elements had been introduced metasomatically into the gneiss. The same data set of the Roffna deformation zone was reinterpreted by Dickin (1988), again by a graphical method of volume/mass balancing. Dickin concluded that the shear zone had undergone some 50% of volume loss during deformation, along with a "catastrophic loss of most major elements and moderate loss of light REE", whereas heavy REE remained "rather immobile on a whole rock scale".

Controversial interpretations of the same set of chemical rock compositions may be rather common, because chemical data alone provide not enough information to give unambiguous results for volume change. This has motivated us to develop a new geochemistry-independent method of volume/mass balancing for shear zones (Steyrer and Sturm, 2002; Sturm and Steyrer, 2003), based on the use of zircon crystals as passive markers and having demonstrated that they form a stable mineral phase during deformation. In applying this method to the Roffna gneiss we then present a model how to solve the above-mentioned controversy.

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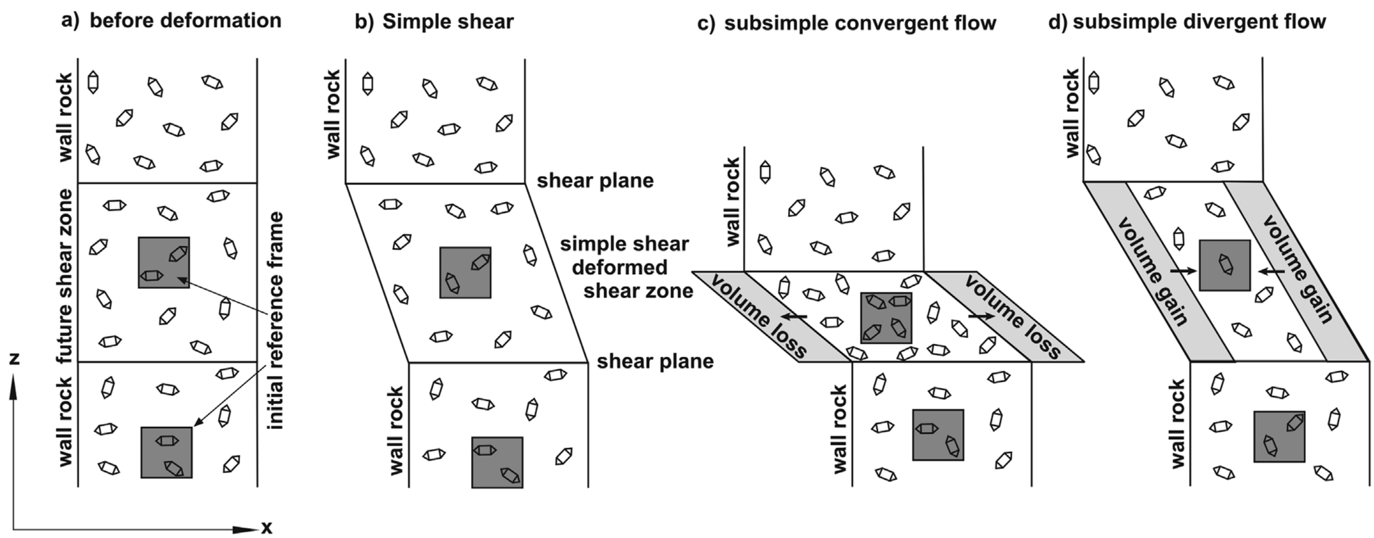

Fig. 1. Sketch of an ideal simple-shear zone visualizing the problem of volume changes from wall-rock (protolith) to highly deformed rock (mylonite). (a) Situation before shearing: Zircon crystals are assumed to be distributed homogeneously, therefore any reference volume (shaded squares) contains ± the same number of zircon crystals (symbolical 2 in this sketch). These zircons are used as passive markers for any volume changes during shearing processes: (b) After shearing, simple shear deformation: the number of zircons per reference volume remains constant, though there is some rotation of the zircon crystals parallel to the shear zone boundary. (c) After shearing, subsimple convergent flow, 50% volume loss: the reference volume has the same size, but the number of the passive markers has doubled (now 4 zircon crystals). (d) After shearing, subsimple divergent flow, 50% volume gain: the reference volume again has the same size, but the number of the passive markers has halved (now only 1 zircon crystal).

1.2. Mass balancing in shear zones – an overview

Many shear zones can be understood as having undergone heterogeneous simple shear (e.g. Simpson, 1983; O'Hara, 1990). Detailed strain analyses of mylonites from shear zones, however, commonly show a flattening-type of finite strain that deviates from plane strain. Since volume loss can be incorrectly attributed to true flattening (Ramsay and Wood, 1973) and volume changes in shear zones are often difficult to quantify, volume loss associated with flattening may be more important than is commonly recognized. Here we propose a new method to determine the contribution of volume loss to finite strain in mylonitic shear zones, by quantifying the content in the stable accessory mineral zircon of both a granitic precursor and its associated mylonites. Zircon crystals are common accessories in granitoids and have the advantage of being very resistant to physical and chemical alterations in low- to medium-grade shear zones (e.g. Wayne and Sinha, 1988; Steyrer and Sturm, 1994; Sturm, 1999). However, zircon grains can be affected to some extent by dissolution and recrystallization at upper amphibolite facies and higher metamorphic grade conditions and under the influence of an acidic fluid phase (e.g. Wayne and Sinha, 1988; Watson, 1996). However, in view of the often reported evidence of zircon dissolution (even at certain weathering conditions), either in form of dissolution pits or rounded corners and edges (Nahon and Merino, 1997 and references therein), the stability of zircon crystals in a deforming granite has to be demonstrated for any given shear zone, prior to quantifying the number densities and of zircon grains in the undeformed wall rock and in the mylonite.

Simple models of volume/mass balance in ductile shear zones were introduced by Voll (1960), who described a passive enrichment of heavy minerals (e.g. apatite, zircon and tourmaline) during pressure solution in high strain domains. Comparable methods have been proposed by Cosgrove (1976) and Behrmann (1986), using the volume balance method for the estimation of finite deformation. Behrmann (1986) considered a model material composed of two phases, one of them being mobile during deformation, while the second, immobile phase would serve as a passive marker in identifying relative gain or loss of volume. The volume change was expressed in terms of a volume factor $f_{V,}$ equal to the ratio of immobile phase available before (c_u) and after deformation (c_d) (equation [1], Behrmann, 1986). In a preliminary study, Sturm and Steyrer (2001, 2003) used zircon crystals as passive volume markers in a deep crustal shear zone, where transpressive deformation of a tonalite developed under medium-grade metamorphic conditions and caused a volume loss of ∼32%.

In order to explain the approach of the present study, we consider a shear zone in which the material deforms by plane strain (Fig. 1a–d) and where displacements remain continuous throughout the shear zone thickness. Changes in volume and chemical composition in the transition from undeformed wall rocks to shear zones and (Fig. 1a) may accordingly be interpreted in one of the following three ways:

1. Constant volume (isochoric) deformation (simple shear *sensu stricto*, Fig. 1b): In this case fluids may or may not percolate through the system. Fluids remaining in the system may cause mineral reactions without changes in bulk chemistry. Evidence for such isochemical/isochoric shearing comes from constant contents of typically mobile components such as noble metals and sulfides in both the protolith and its related mylonite (e.g. Kerrich et al., 1977).
2. Volume loss within the shear zone (subsimple convergent shear zone, Fig. 1c): Several authors have observed that shear zones in granitic rocks often exhibit increasing contents of relatively immobile elements such as Ti, Zr, V, Y and P with increasing deformation (Beach, 1976; Vocke et al., 1987; Selverstone et al., 1991; O'Hara, 1988; Lonka et al. 1998, Goncalves et al., 2016). This suggests a volume loss resulting from the depletion of other more soluble elements during deformation (e.g. Dickin, 1988).
3. Volume gain during deformation (subsimple divergent shear zone, Fig. 1d): This case is marked by high activity of metamorphic fluids that change the rates of chemical and mechanical processes (e.g. Beach, 1976; Hippertt, 1998), thereby influencing the dominant deformation mechanisms (Janecke and Evans, 1988). Under transtensional deformation volume gain within this type of shear zone may occur which is indicated by e.g. quartz veins. Such an increase of mobile elements chiefly occurs during low-temperature deformation and cataclasis (e.g. Hippertt, 1998; Manatschal, 1999), facilitated by a network of open fractures created during brittle deformation.

1.3. Main objectives of the study and open questions

The present study deals with the following four questions: