Journal of Structural Geology 33 (2011) 1728–1750

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Review article

The role of second phases for controlling microstructural evolution in polymineralic rocks: A review

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ARTICLE INFO

Article history:
Received 17 November 2010
Received in revised form
18 August 2011
Accepted 31 August 2011
Available online 22 September 2011

Keywords:
Zener pinning
Second phase
Grain coarsening
Deformation

ABSTRACT

We present a state-of-the-art review of the microstructural evolution in rocks under static and deformational conditions. First, the general concepts and processes are introduced using monomineralic aggregates. Then, they are expanded into the more complex context of polymineralic rocks with a dominant matrix phase. The first part of this contribution delivers information on sample strategies to quantify polymineralic microfabrics. Based on comparisons between microfabrics of monomineralic and polymineralic rocks, we use the common knowledge collected over the past decades for monomineralic systems and discuss the differences to polymineralic ones in terms of microstructures, modal compositions, spatial distribution of phases, crystallographic preferred orientations and associated processes. The article puts particular emphasis on the effect of coupled grain growth, mass transfer processes, and deformation mechanisms. We speculate on the effect of mineral reactions during the evolution of microstructures and rheology in polymineralic aggregates at different metamorphic conditions. At the end of the article, we demonstrate the great potential of grain-size evolution maps as microstructural tool to unravel the geological history of polymineralic rocks that evolved under a variety of geodynamic situations.

1. Introduction

Natural microstructures of rocks are of great importance since they, if stabilized and preserved, provide important information on the physical and chemical conditions during different stages of their evolution (e.g., Handy, 1987, 1989; Bestmann et al., 2000; Jessell et al., 2003; Pearce and Wheeler, 2010). The capability of reading both monomineralic and polymineralic microstructures is therefore crucial to unravel a rock's evolution, allowing the detection of deformation and/or thermal histories (e.g., Ramsay, 1967; Means, 1976; Fischer and Woodward, 1992; Vernon, 2004). In this light, the quantitative analysis of microstructures is paramount including a parameterization of grain sizes, grain-size distributions (also referred to as crystal-size distributions: CSD), SPO (shape-preferred orientation), as well as the spatial distribution of phases. Particularly, grain size plays a fundamental role in this context (Twiss, 1977; Frost and Ashby, 1982; ter Heege et al., 2002). When also CPO (crystallographic preferred orientation) is included in the description, the aggregates are referred to as microfabrics (see Schmid and Handy, 1991). To understand micro-scale processes involved in rock deformation, special attention has been paid to the study of monomineralic aggregates in the early days of microstructural research from an experimental and natural point of view (e.g., Voll, 1960; Hobbs, 1966; Guillopé and Poirier, 1979). In the past decades, an increasing number of investigations dealt with the more complex evolution of polymineralic rocks, a crucial step, given the fact that more than 95 vol.-% of rocks are polymineralic (Burg and Wilson, 1987; Jordan, 1987; Tullis et al., 1991; Handy, 1994; Berger and Stünitz, 1996; Fliervoet and White, 1995; Herwegh and Jenni, 2001; Ji et al., 2001, 2003; Berger and Herwegh, 2004; Barnhoorn et al., 2005b; Dimanov and Dresen, 2005; Ebert et al., 2007a,b; Delle Piane et al., 2009; Wilson et al., 2009; Fusseis et al., 2009; Brodhag and Herwegh, 2010; Linckens et al., 2011a,b).

One approach to parameterize polymineralic rocks is the determination of the volume fractions of different rheological phases (e.g., Handy, 1990; Song and Ree, 2007). Although being successfully applied to partially molten systems (e.g., Rosenberg and Handy, 2005), severe limitations arise because of lacking

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0191-8141/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2011.08.011

information on geometrical aspects like the spatial distribution and interconnectivity of the different phases, their grain sizes or the percolation of fluids/melts through the aggregates (Zu et al., 2011). Such information is mandatory for establishing a proper link between microfabric and resulting rheology (e.g., Handy, 1990, 1992; 1994).

By using nature as a laboratory, we use selected samples to demonstrate how the aforementioned parameters can be measured in microfabrics, allowing microstructural quantification in a reliable manner. The general processes are introduced by focusing first on nearly monomineralic aggregates expanding then into the more complex interactions in the case of polymineralic aggregates. We will introduce some concepts on the base of monomineralic aggregates and expand them to polymineralic rocks using carbonates and peridotites as two prominent representatives of crustal and mantle rocks. The principles presented, however, do apply for all polymineralic microfabrics with a volumetrically dominant matrix phase.

2. Meso- to large-scale investigations

Large-scale deformation is controlled by microstructural processes, which are driven by minimization of internal free energy owing to changes in physico-chemical conditions, for example temperature, strain, flow stress/strain rates and chemical potentials (e.g., Regenauer-Lieb and Yuen, 2003; Herwegh and Berger, 2004). To learn more about the link between microfabric and meso- to large-scale structures two approaches have been followed in the past: (i) studies on the meso-scale (several meters to tens of meters) and (ii) investigations on the large-scale (kilometers).

(i) Particularly the study of meso-scale structures, like shear zones, is appealing, because often strain gradients along and across shear zones can be used in the sense of Means (1995) to infer the evolution of microstructures with increasing shear strain (Ramsay, 1980; White et al., 1980; Hudleston, 1980; Watts and Williams, 1983; Fusseis et al., 2006; Warren and Hirth, 2006; Oesterling et al., 2007; Toy et al., 2009; Schrank et al., 2008; Skemer et al., 2010). However, the study of meso-scale structures faces the problems of the estimation of absolute deformation temperatures and potential retrograde reactivation. Also, information on the time interval of the activity of such small and short-lived structures is critical but would be mandatory to unravel strain rates and to learn more about the associated process rates (Schrank et al., 2008).

(ii) Studies on large-scale structures can deliver more reliable information (large-scale shear zones, contact metamorphic aureoles, regional metamorphism) by combining information on gradients in temperature, shear strain or strain rate with corresponding sampling strategies. Despite some uncertainties of some of these parameters, large sample series along the structures will result in statistically robust datasets on relative changes of these parameters, because potential local variations and uncertainties will be cancelled out (Handy, 1987; Dunlap et al., 1997; Stipp et al., 2002b; Herwegh and Pfiffner, 2005; Ebert et al., 2008; Toy et al., 2008). On the kilometer-scale, pronounced temperature gradients can be unraveled using different geothermometers, which can result in reliable temperature estimates (Herwegh and Berger, 2003; Herwegh and Pfiffner, 2005; Ebert et al., 2008; Grujic et al., 2009; Linckens et al., 2011a). In large-scale shear zones, sampling profiles along the transport direction allows to track down microstructural variations as a function of changing temperature, stress and strain rate conditions representing a field laboratory in which the processes can directly be compared to experimental and theoretical data (e.g., Dunlap et al., 1997; Stipp et al., 2002a; Herwegh et al., 2005b; Mehl and Hirth, 2008). In the ideal case, knowledge of the total displacement, the shear zone width and the time interval of deformation may allow the calculation of strain rates. Even with the common uncertainties related to the time interval of deformation, at least the order of strain-rate magnitude can be obtained by following this strategy. Ideally, such sample series are accomplished by sample profiles across the shear zones, by which potential shear gradients or the retrograde shrinkage of the shear zone may become visible (e.g., Herwegh and Pfiffner, 2005; Ebert et al., 2007b; Austin et al., 2008; Herwegh et al., 2008).

3. Quantitative description of microfabrics

The proper description of microfabrics requires not only the grain sizes and the abundance of the different phases but also information on their chemical compositions, spatial distributions and geometric relationships (e.g., Turner and Weiss, 1963; Jerram et al., 1996; Jerram and Higgins, 2007). Since these parameters can vary laterally in a substantial manner, a definition of microstructural *R*epresentative *E*lementary *V*olume (REV) is required (e.g., Schrank et al., 2008; Liu et al., 2009), where the sizes, abundance and distributions of the phases can be considered to be constant. From a statistical point of view, the REV must be large enough to cover a couple of hundred grains. Therefore, quantitative descriptions of different REV are mandatory, requiring the application of automated analysis techniques. At first glance, picking the REV by eye is a valid approach because human's inspection is rather efficient. During data processing, the statistical relevance has to be evaluated in terms of each individual data set per REV but also for the overall database. In this work, mineral type, size, aspect ratio, perimeter, orientation, volume fraction and grain center of each individual grain were quantified for all phases with image analysis software (Berger et al. this volume). Based on these measurements, area- and number-weighted grain-size distributions, volume fractions of the different phases, grain-shape preferred orientations and nearest-neighbor relationships can be obtained. The geometrical spacing of phases is crucial, because it contributes to how and at which rate chemical processes can occur and over which distances mechanical responses due to the presence of a specific phase are expected to occur. In this sense, the selection and definition of REV is rather crucial allowing the discrimination of chemically or mechanically variable microstructures. Note that in the entire review we restrict to the 2D space, leaving space for future studies in the more complex 3D world (Fusseis et al., 2009; Zu et al., 2011; Berger et al., this volume).

4. Spatial distribution of mineral phases and their presentation in the Zener space

In a polymineralic rock with dominant matrix phase (matrix phase volume fraction > 0.5), the occurrence of chemical impurities and/or other minerals, the so-called second phases, will influence different physico-chemical processes. These processes are subdivided into those acting at interfaces between matrix mineral and second phase, or those affecting solely the matrix phase. The resulting "bulk" microstructure, especially the stable grain size in the case of mylonites, represents the balance between grain-size reduction and grain growth, i.e. reflect a microstructural equilibrium (Herwegh and Berger, 2004; Austin and Evans, 2007, 2009). In all examples with initial grain sizes below the equilibrium grain size, the grain boundary mobility will influence the way and the