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Strain rate dependent calcite microfabric evolution – An experiment carried out by nature

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ABSTRACT

A flanking structure developed along a secondary shear zone in calcite marbles, on Syros (Cyclades, Greece), provides a natural laboratory for directly studying the effects of strain rate variations on calcite deformation at identical pressure and temperature conditions. The presence and rotation of a fracture during progressive deformation caused extreme variations in finite strain and strain rate, forming a localized ductile shear zone that shows different microstructures and textures. Textures and the degree of intracrystalline deformation were measured by electron backscattered diffraction. Marbles from the host rocks and the shear zone, which deformed at various strain rates, display crystal-preferred orientation, suggesting that the calcite preferentially deformed by intracrystalline-plastic deformation. Increasing strain rate results in a switch from subgrain rotation to bulging recrystallization in the dislocation-creep regime. With increasing strain rate, we observe in fine-grained (3 μm) ultramylonitic zones a change in deformation regime from grain-size insensitive to grain-size sensitive. Paleowattmeter and the paleopiezometer suggest strain rates for the localized shear zone around 10^{-10} s^{-1} and for the marble host rock around 10^{-12} s^{-1}. We conclude that varying natural strain rates can have a first-order effect on the microstructures and textures that developed under the same metamorphic conditions.

1. Introduction

Crystal-plastic deformation of calcite has been the focus of many experimental studies. Different initial grain sizes, strain rates, stresses, temperatures, dry/wet conditions and CO_2 partial pressures have been considered to investigate a wide range of deformation regimes (e.g. Schmid et al., 1980; Schmid et al., 1987; Rutter, 1995; De Bresser and Spiers, 1997; Pieri et al., 2001; Barnhoorn et al., 2004; Barber et al., 2007; Llana-Fúnez and Rutter, 2008; Liteanu et al., 2012; Rybacki et al., 2013). Flow laws for the dislocation and diffusion creep fields have been determined with respect to strain rates, stresses and temperatures (e.g. De Bresser et al., 2002; Renner et al., 2002; Herwegh et al., 2003). Twinning on e-planes seems to be common during deformation of calcite rocks at temperatures below 400 °C (Ferrill et al., 2004). For crystallographic reasons total twinning in calcite would lead to a shear strain of $\gamma = 0.69$, under the simplifying assumption that the twin plane is oriented parallel to the shear-zone boundary (Schmid et al., 1987). Therefore, increasing strain requires the additional activation of intracrystalline slip (Rybacki et al., 2013). Textures developed at small strain ($\gamma < 2$) are similar in a wide temperature range while at greater strain, textures vary with increasing temperature (Barnhoorn et al., 2004). Flow laws and deformation-mechanism maps suggest preferential deformation by grain-size sensitive mechanisms (GSS) at small grain sizes, whereas coarse-grained rocks deform by dislocation creep (Schmid et al., 1987).

Complementary to experimental studies, textural and microstructural investigations of natural calcite marbles characterized shear sense, flow type, deformation mechanisms, and pressure and temperature conditions (Vernon, 1981; Ratschbacher et al., 1991; Kurz et al., 2000; Bestmann et al., 2000, 2003, 2006; Trullenque et al., 2006; Oesterling et al., 2007; Austin et al., 2008). These studies also document a switch from twinning to dislocation creep regime with increasing strain. Recrystallization by subgrain rotation (SGR) and less common bulging (BLG) result in grain size reduction, which is often followed by the activation of GSS creep. However, a direct comparison of experimentally and naturally deformed calcite remains difficult because of the extreme difference between experimental and natural strain rates (Paterson, 1987).

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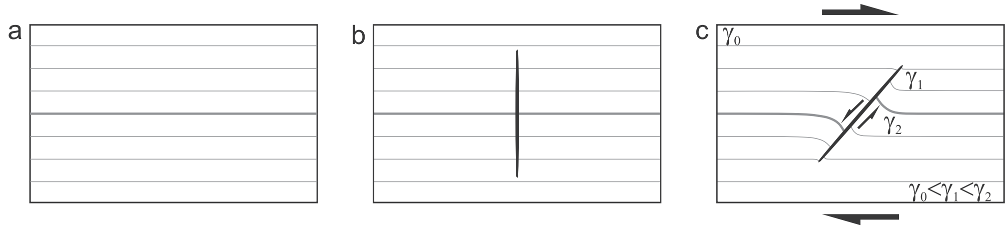

Fig. 1. Schematic sketch of the development of an a-type flanking structure. a. Foliated host rock. b. A crack develops perpendicular to the host-rock foliation. c. Due to shearing the crack (i.e. CE) rotates, resulting in an antithetic offset along the crack. Note that the displacement of marker lines varies along the cross-cutting element (CE) leading to a spatial variation in strain (γ).

In this study, we investigate deformation mechanisms within and outside the cross cutting element of a flanking structure developed in almost pure calcite marbles on Syros (Cyclades, Greece). Such a structure forms, when a planar inclusion of finite length (i.e. the cross cutting element, CE) deforms within a host rock resulting in the rotation of the CE and slip along it (Grasemann and Stüwe, 2001; Passchier, 2001). Due to the slip gradient along the CE, a heterogeneous strain field in the surrounding area causes marker layers to deform by normal and/or reverse drag (Reches and Eidelman, 1995; Passchier, 2001; Grasemann et al., 2005). Coeval with flanking fold development at low shear strain, deformation within the CE may record shear strain and strain rates, which are much greater than these background values (Grasemann et al., 2011, Fig. 1). The flanking structure on Syros thus represents a natural experiment, where a specific marble was deformed at relatively small strain rates in the host rock and at much greater strain rates within the CE under the same metamorphic conditions. The current study documents calcite microfabric evolution for natural geological conditions, providing the opportunity to study deformation and recrystallization mechanisms of calcite as a function of strain and strain rates. The consistency of experimentally determined flow laws, piezometer and paleowattmeter are tested with parameters derived from the calcite samples, which deformed under natural conditions.

2. Geological setting

The island of Syros (Greece) is part of the Cycladic blueschist belt that is situated in the back-arc of the Hellenic subduction zone, where the African plate is subducted northward beneath Eurasia (Papanikolaou, 1987; Wortel et al., 1993; Ring et al., 2003). In the Cycladic area, three main units can be distinguished, separated by tectonic contacts: (1) the para-autochtonous Basement Unit consisting of metasediments and orthogneisses, (2) the Cycladic Blueschist Unit (CBU) composed of metasediments and metabasites, and (3) the Upper Unit made up of ophiolitic rocks, sediments and pre-Eocene metamorphic rocks (Bonneau, 1984; Robertson and Dixon, 1984). Two main metamorphic events

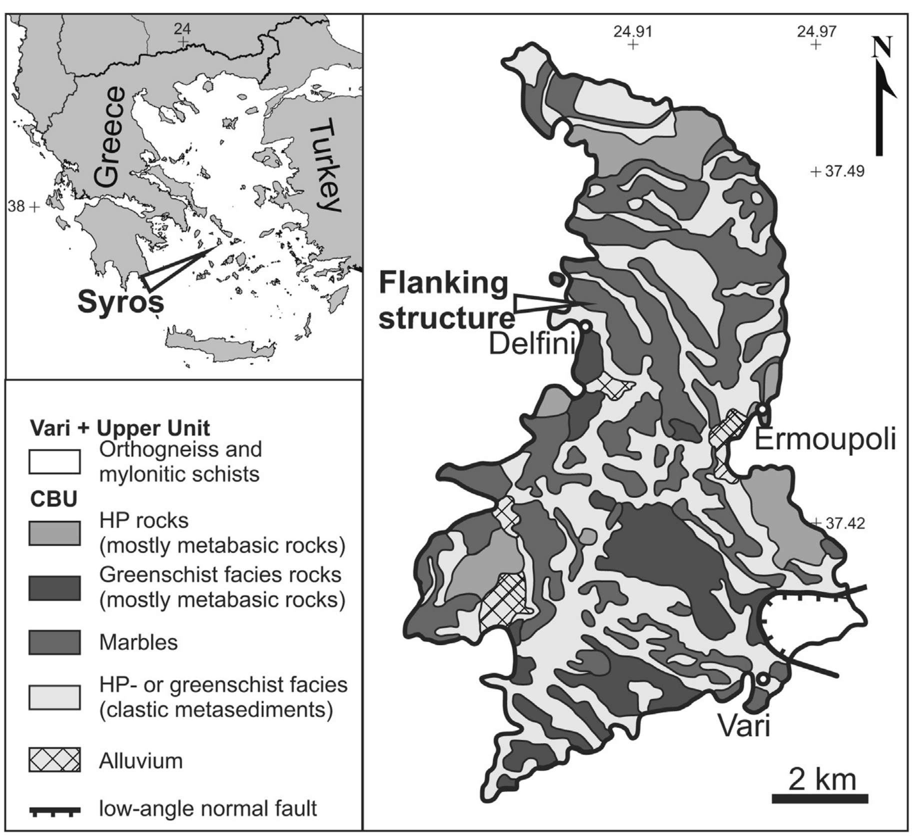

Fig. 2. Geological map of Syros (modified after Keiter et al. (2004)). The arrow points to the location of the outcrop.