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Heterogeneous constrictional deformation in a ductile shear zone resulting from the transposition of a lineation-parallel fold

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ABSTRACT

We use new (micro-)structural, petrofabric, strain and vorticity data to analyze the deformation path in a mesoscopic quartz mylonite zone. The mylonite zone resulted from the complete transposition of a stretching lineation-parallel isoclinal fold. Symmetric cleft-girdle quartz c-axis fabrics were recorded in the middle domain, which occupies the inner limbs of the precursor isoclinal fold, while asymmetric cleft- and crossed-girdle fabrics were observed in the upper and lower domains that represent the outer limbs. Constrictional strain, with increasing *k* values towards the middle domain, is inferred from petrofabric and 3D strain data. Oblique grain shape fabrics yield vorticity estimates of 0.72–0.90 in the zone. However, in the middle domain, pure shear dominated deformation is suggested by orthorhombic crystallographic fabrics. Strain rate is constant throughout the zone; a strain decrease towards the zone center implies that deformation ceased earlier in the middle domain. The data indicates that fold transposition and subsequent mylonitization started as pure-shear-dominated constrictional deformation and progressively changed to simple-shear-dominated, plane strain. During this flow path the asymmetric quartz c-axis fabrics likely developed by depopulation of cleft-girdle maxima rather than from the synthetic rotation of fabric maxima itself.

1. Introduction

Strain localization in polydeformed metamorphic belts commonly is achieved by the development of a transposition foliation axial planar to tight – isoclinal folds of a preexisting foliation (e.g. Tobisch and Patterson, 1988; Mawer and Williams, 1991). The progressive strain accumulation causes the new axial planar foliation to form a single penetrative or mylonitic foliation, and leads to the full transposition and dismembering of the related isoclinal fold. Transposed folds within such high-strain domains are generally recumbent (Williams et al., 2006) and often oriented with their hinge lines approximately parallel to the stretching lineation. This co-linearity between fold hinges and stretching lineation may result either from folds which were generated oblique to lineation and subsequently rotated towards the transport direction during intense non-coaxial shearing (Escher and Watterson, 1974; Williams, 1978; Alsop, 1992), or from shearing of a moderately or steeply dipping planar fabric oriented at low angle to the stretching direction (Stünitz, 1991; Froitzheim, 1992; Fletcher and Bartley, 1994; Fossen, 2010, p. 267). The second folding mechanism can occur under various deformation modes, including a pure or simple shear strain path and constrictional to flattening 3D strain states (Fig. 1).

Quartz crystallographic fabrics have been used extensively as qualitative vorticity and 3D strain gauges to distinguish the deformation mode associated with the development of tight – isoclinal folds occurring in different scales from microscopic to regional (Carreras et al., 1977; Brunel, 1980; Law, 1990; Stünitz, 1991; Crispini and Capponi, 1997; Lebit et al., 2002; Lagoeiro et al., 2003; Fernández et al., 2007; Morales et al., 2011). Many of these petrofabric studies, coupled with strain analyses, reveal a spatially heterogeneous and complex deformations characterized by different components of simple shear and different 3D strain types in the various fold domains. This complexity could be attributed to the varying degrees of rotation and the varying rates of resetting of the preexisting fabrics in the domains. Therefore, quartz crystallographic fabrics and strain data obtained from folds do not provide a reliable record of the externally imposed kinematic framework that controlled the fold growth. This problem could be resolved by investigating completely transposed folds in high-strain zones. We are aware of only a single study from such zones (e.g. Hongn and

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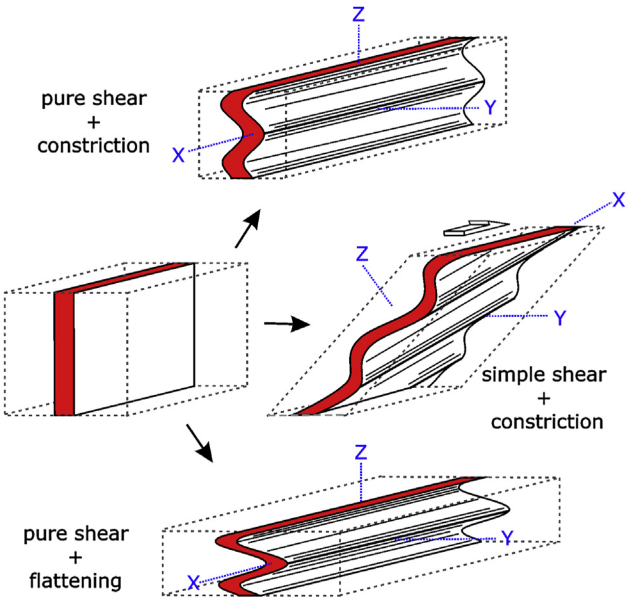

Fig. 1. Hypothetical case examples showing shearing of a steeply dipping plane striking (sub-)parallel to the stretching direction under various deformation modes. Folds parallel to the stretching direction develop in all cases (based on Stünitz, 1991; Froitzheim, 1992; Fossen, 2010, p. 267).

Hippertt, 2001). The question remains whether crystallographic quartz fabrics, even in mylonitic zones, retain information of any earlier folding events (Hongn and Hippertt, 2001) or only record deformation of the mylonitization event (Brunel, 1980).

This study analyzes an outcrop-scale ductile shear zone, the Aetopetra shear zone, that developed during the mylonitization of a fully transposed fold. The fold precursor to the shear zone initiated with its hinge line parallel to the transport direction due to shearing of a preexisting steeply inclined foliation oriented nearly parallel to the stretching direction. We present new (micro-) structural, quartz petrofabric, strain and vorticity data from the shear zone. Based on the strain memory of the various fabrics, these data define the spatial and temporal heterogeneity of deformation associated with the growth of this type of shear zone.

2. Geological and structural framework

The Aetopetra shear zone is located on the southeastern part of Evia Island, Greece, where the Blueschist Unit rocks of the Cycladic Massif are exposed (Fig. 2a and b). The Cycladic Massif, part of the Internal Hellenides, exposes nappes and units that were juxtaposed during the Alpine orogeny. Within the Cycladic nappe pile, the Blueschist Unit occupies an intermediate position and contains two main nappes (e.g. Dürr, 1986; Xypolias et al., 2010): (1) the structurally higher Ochi Nappe that is comprised of quartzofeldspathic schists, calcschists, basic meta-volcanogenic rocks and minor meta-ultrabasic rocks, and (2) the lower Styra Nappe that is comprised of pelitic schists and marbles with quartzite intercalations (Fig. 2c and d). Rocks of both nappes underwent a common metamorphic history that includes an Eocene (ca. 50–40 Ma) epidote – blueschist facies metamorphism ($T_{max} = 450$ °C; $P_{min} = 11$ kbar) followed by a greenschist to pumpellyite–actinolite facies overprint ($T = 350$ °C; $P = 4$–7 kbar) at the Oligocene–Miocene boundary (ca. 25 Ma) (c.f. Maluski et al., 1981; Katzir et al., 2000).

The Blueschist Unit records a polyphase deformation history that includes at least three major phases of ductile deformation (see Xypolias et al., 2012 for details). The earliest deformation phase was contemporaneous with the high-pressure metamorphism and is expressed by a foliation that is strongly developed to mylonitic and an ESE-trending stretching lineation. The stretching lineation was formed during ESE-directed thrusting that led to the emplacement of the Ochi over the Styra Nappe (Fig. 2d). Subsequent constrictional deformation during the early exhumation stage is recorded in outcrop to map-scale, open to tight, upright folds that deform the earlier foliation and the contact between the Ochi and Styra Nappes (Fig. 2d). The Aetopetra shear zone formed during the third phase of ductile deformation under transitional blueschist-greenschist to greenschist-facies conditions. This deformation phase is recorded by a planar fabric that varies in intensity from a widely spaced crenulation cleavage to a penetrative mylonitic foliation, and by a well-developed, ENE–trending stretching lineation (Fig. 2c). The cleavage/foliation planes are commonly axial planar to open to isoclinal, recumbent or gently-inclined folds with hinge lines trending (sub-) parallel to the stretching lineation (Fig. 2c and d). Previous study in the area has showed that the co-linearity of the fold hinge lines and the stretching lineation resulted from vertical shortening of moderately or steeply dipping planes (earlier foliation) oriented at low angles to the stretching direction during a pure-shear-dominated deformation (Xypolias et al., 2012). Note that variations in foliation intensity result from the localization of deformation into ENE-directed ductile shear zones. A series of such thrust-shear zones are shown in map of Fig. 2b. The most representative thrust-shear zone is the Aetopetra shear zone that overprints major folds and transposes the nappe contact developed during the earlier deformation phases (Fig. 2d).

3. Structure of the Aetopetra shear zone

The Aetopetra shear zone can be traced over a map length (along strike) of 6.5 km and is defined by 1- to 5-m-thick mylonites derived from rocks of the Styra and Ochi Nappes (Fig. 2c and d). It occupies the central part of a ca. 300-m-thick zone of localized deformation that resulted from isoclinal folding and transposition of an early steep foliation into a gently dipping foliation (Fig. 2d). Footwall and hanging-wall rocks of the shear zone are characterized by a well-developed ENE-trending stretching lineation oriented (sub-)parallel to the hinge lines of tight to isoclinal folds (Fig. 2c) and by a heterogeneously developed planar fabric with textures ranging from a closely-spaced axial planar crenulation cleavage to a strongly developed foliation. However, the intensity of foliation tends to increase towards the Aetopetra mylonitic zone. Most of the strongly sheared rocks observed in the field can be qualitatively classified as $L = S$ or $L > S$ tectonites. Mylonitic rocks are also present in thin parallel bands several tens of meters from the Aetopetra shear zone. These ca. 0.5-m-thick mylonitic bands in the hanging-wall of the shear zone are associated with a system of four minor ductile shear zones that cut across the axial plane of major gently-inclined folds or shear-out the common limb of antiform–synform pairs. These shear zones restacked the early thrust and fold sequence and place the Styra Nappe rocks over Ochi Nappe rocks (Fig. 2d).

The thickness of the Aetopetra mylonites generally increases towards the central part (in map view) of the shear zone where a 2-m-thick band of mylonites derived from the meta-volcanogenic rocks of the Ochi Nappe are stacked on top of 2.1-m-thick mylonitized quartzites of the Styra Nappe (Fig. 3a and b). The stretching lineation within both mylonite horizons has a fairly constant orientation parallel to the regional ENE-trending lineation. In meta-volcanogenic mylonitic rocks, the stretching foliation is defined by aligned green and/or blue amphibole needles and by strain shadows around pyrite and feldspar porphyroclasts; in quartzite mylonites, it is defined by stretched quartz rods and thin aligned streaky mica and chlorite aggregates. The contact between these two mylonite