Journal of Structural Geology 69 (2014) 75–90

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Mechanisms of flexural flow folding of competent single-layers as evidenced by folded fibrous dolomite veins

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
25 September 2014
Accepted 3 October 2014
Available online 15 October 2014

Keywords:
Fibrous dolomite veins
Flexural flow folding
Strain distribution
Vein fabric
Viscosity contrast

ABSTRACT

Flexural flow is thought unlikely to occur in naturally deformed, competent isotropic single-layers. In this study we discuss a particular case of folded bedding-parallel fibrous dolomite veins in shale, in which the internal strain pattern and microstructural deformation features provide new insights in the mechanisms enabling flexural flow folding. Strain in the pre-folding veins is accommodated by two main mechanisms: intracrystalline deformation by bending and intergranular deformation with bookshelf rotation of dolomite fibres. The initially orthogonal dolomite fibres allowed a reconstruction of the strain distribution across the folded veins. This analysis shows that the planar mechanical anisotropy created by the fibres causes the veins to approximate flexural flow. During folding, synkinematic veins overgrow the pre-folding fibrous dolomite veins. Microstructures and dolomite growth morphologies reflect growth during progressive fold evolution, with evidence for flexural slip at fold lock-up. Homogeneous flattening, as evidenced by disjunctive axial-planar cleavage, subsequently modified these folds from class 1B to 1C folds. Our study shows that the internal vein fabric has a first-order influence on folding kinematics. Moreover, the fibrous dolomite veins show high viscosity contrasts with the shale matrix, essential in creating transient permeability for subsequent mineralising stages in the later synkinematic veins during progressive folding.

1. Introduction

The kinematics of folding of competent single-layers has been intensely studied, showing significant complexity in strain accommodating mechanisms during folding, primarily due to a complex interplay of layer thickness, rheology contrast, degree of anisotropy, progressive changes in mechanical properties, strain rate and other parameters (e.g. Ramsay, 1967; Fletcher, 1974; Shimamoto and Hara, 1976; Treagus and Treagus, 1981; Schmalholz and Podladchikov, 1999, 2001; Schmid and Podladchikov, 2006; Hobbs et al., 2008, 2010; Kocher et al., 2008; Huang et al., 2010; Schmid et al., 2010). Nevertheless, a number of ideal reference cases is put forward for the internal strain distribution in symmetrically buckled, competent, isotropic single-layers within a viscous or power-law matrix. These are typically tangential-longitudinal strain, flexural flow and flexural slip (Ramsay, 1967; Hudleston and Lan, 1993; Bastida et al., 2003; Bobillo-Ares et al., 2006; Twiss and Moores, 2007).

Natural examples of folded, competent, isotropic single-layers in an incompetent viscous matrix generally show a strain distribution compatible with dominant tangential-longitudinal strain (Hudleston and Treagus, 2010; Evans and Fischer, 2012). Using numerical modelling, Hudleston et al. (1996) demonstrated that only the aggregate response of a highly anisotropic medium may approximate that of pure flexural flow. However, extremely high anisotropy parallel to the shear plane is normally only seen in incompetent layers, such as slates or phyllites with a pervasive slaty cleavage fabric. This lead Hudleston et al. (1996) to question whether flexural flow actually occurs in naturally folded, competent single-layers.

In order to understand the kinematics and strain accommodating mechanisms during folding of single-layers in a viscous or power-law matrix, intensive numerical modelling efforts were carried out in the last decade (e.g. Schmalholz and Podladchikov, 2000, 2001; Kocher et al., 2006; Schmalholz, 2006, 2008; Hobbs et al., 2008, 2010; Schmid et al., 2010; Huang et al., 2010; Hobbs and Ord, 2012; Schmalholz and Schmid, 2012). Many of these studies investigate how anisotropy within single-layers and the

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http://dx.doi.org/10.1016/j.jsg.2014.10.002

geometry of multiple transversely isotropic layers influences the folding instability and kinematics (e.g. Lan and Hudleston, 1996; Fletcher, 2005; Toimil and Griera, 2007; Kocher et al., 2008). From these studies, it is clear that the assumption of mechanical isotropy within single layers is an oversimplification, often with important influence of anisotropy both along and across competent single-layers, or in an aggregate response. In addition, we know that the internal fabric of folded single-layers in nature, in particular that of veins, shows significant complexity (Zhang et al., 1993; Hippertt and Tohver, 2002; Kocher et al., 2006; Toimil and Fernández, 2007; Toimil and Griera, 2007). It is, though, to date still poorly understood how exactly the internal fabric influences folding.

In this study we focus on folded bedding-parallel, fibrous dolomite veins in shale. We aim to constrain the fold kinematics by which strain is accommodated in these veins, quantify the internal strain distribution and estimate the rheology at the time of deformation. Because the initial fabric of the folded fibrous veins is known, it allows to study how the internal microfabric influences the folding mechanism and quantify how much the fabric controls strain accommodation during folding. The study thus contributes to a better understanding of the role of the internal fabric and anisotropy during folding of competent single-layers.

Finally, folding is important in creating transient permeability structures and the associated mobility of fluids. Therefore, a good understanding of strain-accommodating mechanisms during folding is necessary to constrain fluid mobility (Evans and Fischer, 2012). In this respect, the microstructural observations of this study can provide better insights in the origin/development of the well-constrained sediment-hosted copper–cobalt ore deposits in the study area (Brems et al., 2009; Muchez et al., 2010).

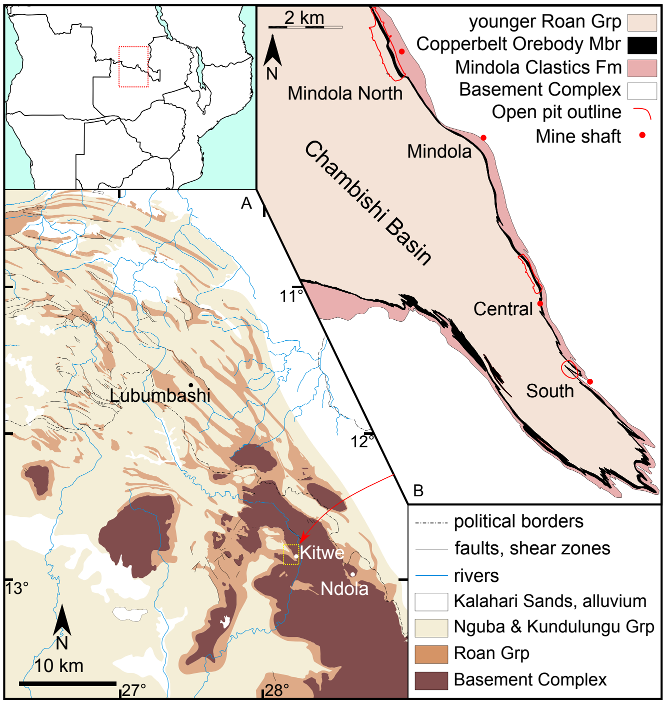

Fig. 1. (A) Schematic geological map showing the Central African Copperbelt, straddling the border between Zambia and the Democratic Republic of Congo. Geology is compiled from several sources (Mendelsohn, 1961a; François, 1974; Thieme and Johnson, 1981). The inset shows the position of this map in Central Africa. (B) Geological map of the southeast end of the Chambishi synformal basin, modified after an unpublished 2008 geological map of Mopani Copper Mines Plc. Four mine shafts and three open pits are indicated. Mbr: Member; Fm: Formation; Grp: Group.

2. Geological setting

The study area is situated in the region of the Nkana stratiform Cu–Co deposit, near Kitwe, Zambia (Fig. 1; Mendelsohn, 1961a; François, 1974; Thieme and Johnson, 1981). The rocks belong to the Neoproterozoic Katanga Supergroup of the Central African Copperbelt, further subdivided into Roan, Nguba and Kundulungu Groups (Cailteux et al., 2005; Bull et al., 2011). They were deformed during the Pan-African, Lufilian orogeny, dated at ~560 Ma to ~500 Ma (Porada and Berhorst, 2000; Hitzman et al., 2012). Peak regional metamorphism, reaching upper greenschist to lower amphibolites facies, occurred ~530 Ma (John et al., 2004; Rainaud et al., 2005; Selley et al., 2005).

The Nkana deposit is situated in the southeastern limb of the Chambishi synformal basin, amidst the Kafue basement inlier (Fig. 1). Folding at the Nkana deposit is poly-harmonic with multiple orders of folding ranging from 1st order folding at basin scale (Croaker, 2011) over 2nd order hectometre-scale folds to 3rd order metre-scale parasitic folding in the more competent units. Folding at the 2nd and 3rd order is by doubly plunging tight to isoclinals folds.

The veins described in this study occur in the Copperbelt Orebody Member of the Katanga Supergroup. This member represents the first transgressive stage overlying siliciclastic red-bed sediments of the Mindola Clastics Formation, related to continental rifting (Selley et al., 2005; Bull et al., 2011). The Copperbelt Orebody Member is a carbonaceous shale to siltstone with a pronounced shaly fabric at Nkana Central and South (Fig. 1). A strong bedding-parallel S_1 cleavage is developed in this carbonaceous shale lithofacies. Conversely, an axial planar S_2 cleavage is in general only weakly developed. However, in some higher-strain parts of Nkana South and Nkana Central, this S_2 cleavage is more strongly developed. Overlying the Copperbelt Orebody Member is a layer-cake stratigraphy of siliciclastics, dolomites and evaporates (Selley et al., 2005).

3. Vein generations

Several vein generations occur in the deposit, previously studied with respect to the metallogenetic model of the ore deposit (Brems et al., 2009), the geochemistry of Cu–Co mineralising fluids (Muchez et al., 2010), REEY characteristics of the gangue carbonates (Debruyne et al., 2013) and the source of metals (Van Wilderode et al., 2013). Veins are most abundant in the carbonaceous shale to siltstone facies in the south of the Nkana deposit (Fig. 1).

In this study, we focus on the two earliest vein generations at Nkana. The earliest, type I veins are pre-folding, bedding-parallel fibrous dolomite veins (Fig. 2). These monomineralic veins are continuous for several meters along strike. A second bedding-parallel generation, type II veins, is typically overgrowing type I veins, but also occurs as separate veins. Contacts of type II veins with the host rock are generally tortuous.

4. Mineralogy and growth morphologies of type I and II veins

Petrographic and microstructural observations were carried out on 82 oriented thin sections that were obtained in a new field campaign (2012), in addition to 76 thin sections available from an extensive sample collection of two previous studies at Nkana (Brems et al., 2009; Muchez et al., 2010). Cold cathode luminescence (CL) was carried out using a Techosyn Cold Cathode Luminescence Model 8200 Mk II (KU Leuven) combined with a Nikon microscope and a ProgRes C10 image capturing system. Working conditions were between 7–13 kV and 400–900 μA with a beam width of 5 mm at a vacuum of 5.5 Pa. Image capture time varied greatly to represent the view under the microscope, and images in