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Numerical modeling of mullions in the Taili high deformation zone, North China: Implications for the rheology of granitic rocks

Zhiyong Li [a,b,*], Zuoxun Zeng [a], Adil S. Mohammed [a]

[a] School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
[b] Global Tectonic Research Center, China University of Geosciences, Wuhan 430074, China

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ABSTRACT

This paper presents a combined field measurement and finite element modeling analysis of the mullions occurring on the contact of two granitic rocks with different grain size in the Taili High-Strain Deformation Zone (THDZ), West Liaoning of North China. All of the field data are located in the plot zone of the modeling results. Numerical modeling results indicate that: (1) The inter-angle between the tangent lines cross the cusp point and the ratio R of amplitude and width of mullions are the most effective parameters to describe the geometric shape and evolution of mullions, as well as useful indicators of the rheology of rocks. (2) The competence contrast controls the growth rate of mullions under shortening. It determines the possible ratio R of final mullions. Moreover, decreasing of the cusp angle in high competence contrast materials is faster than that in low competence contrast model. (3) The initial disturbance is an essential factor for the generation of mullions. Those contacts with higher initial disturbance will develop into mullions more easily and have a high growth rate during the same shortening deformation regime. (4) The rheology and deformation behavior of the granitic rocks in the study area are primarily controlled by the grain sizes of quartz and feldspar. The effective viscosity ratio of biotite adamellite and granitic gneisses is about 0.01–0.5. The deformation mechanisms of these granitic rocks should be dominated by a grain-size-sensitive diffusion creep.

1. Introduction

Mullions are deformation structures consisting of rounded lobes and sharp cusps which developed on the contact of layers with different competence by layer parallel shortening (Smith, 1975; Fletcher, 1982; Sokoutis, 1987). They differ from buckle folds in having shorter wavelengths and are restricted to a single layer interface. Mullions are more common in the clastic strata, typically on the contact of psammite and pelite layers (Kenis et al., 2004, 2005) and are used to denote the more competent material.

Smith (1975) first introduced a general linear hydrodynamic stability theory to describe the onset of folding, boudinage and inverse folding, as well as mullions, in single Newtonian layers. He suggested that all the structures are caused by a same mechanism, a secondary flow driven by an interfacial discontinuity in normal stress during shortening parallel to layers, and the non-Newtonian flow both increases the growth rates and alters the dominant wavelengths of mullions (Smith, 1977). Sokoutis (1987, 1990) performed a series of physical experiments to model the development of mullions at single and double interfaces of non-Newtonian fluids with a low effective viscosity ratio. The experiments modeled the growth rate of amplitude of mullions with different ratios of initial wavelength and initial thickness. However, in all of his experiments, the viscosity ratio and initial amplitude were the same. The affects of viscosity ratio and initial disturbance on the generation of mullions were not considered.

Single interface mullions are well developed on the interfaces of granitic rocks in the Taili High Deformation Zone, North China. These mullions probably reveal the rheology properties of granitic rocks. Although a large number of experimental data on the rheological parameters of granitic rocks exists under laboratory conditions, especially about the partially-molten synthetic granitic rocks (Arzi, 1978; Bagdassarov and Dorfman, 1998a, 1998b; Mecklenburgh and Rutter, 2003), the assessment of paleo-rheology parameters for granitic rocks in nature is relatively scarce.

In this study, we introduce a geometric model to describe the shape of mullions and present a combined detailed field study on the geometry and finite element modeling study of mullions

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* Corresponding author at: School of Earth Sciences, China University of Geosciences, Wuhan 430074, China.

E-mail addresses: zhiyong.li@cug.edu.cn (Z. Li), zuoxun.zeng@126.com (Z. Zeng), adil.geology@gmail.com (A.S. Mohammed).

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developed on the interface of granitic rocks. The numerical modeling results may indicate the deformation mechanism of mullions and attempt to offer a paleo-rheological gauge to constrain the relative viscosity of the granitic rocks with different mineral composition and grain size in nature.

2. Mullions in the Taili high deformation zone

The study area is geographically located in the Xingcheng-Taili region of the western Liaoning province in northeastern China, and tectonically in the eastern part of the northern margin of the eastern North China Craton (Liang et al., 2015a, 2015b, Fig. 1). It extends for several square kilometers and consists chiefly of three distinct lithologic granitic units: Late Neoarchean grey granitic gneiss (2522 ± 21 Ma, zircon U-Pb, Zheng et al., 2009), Late Triassic dark biotite adamellite (~220 Ma, zircon U-Pb, Li et al., 2013) and Late Jurassic light granite (~153 Ma, Li et al., 2013), and, in addition, rare mafic lamprophyric dikes. The Late Neoarchean granitic gneisses consists essentially of quartz (20–35%), microcline (25–40%), plagioclase (15–35%), and biotite (~5%), with accessory amounts of epidote, zoisite, magnetite, etc. (Cai et al., 2014). The biotite adamellite rocks exhibit a porphyritic texture. The large phenocrysts are composed of alkali feldspar and quartz. The matrix is composed of fine-grained minerals, quartz (25–35%), microcline (30–40%), plagioclase (25–30%), and biotite (~5%), with accessory amounts of zircon, garnet, magnetite, apatite, etc. (Li et al., 2013).

The intrusion of biotite adamellite into the late Neoarchean granitic gneisses caused partial remelting and migmatization at the contact zone. Strong ductile deformation occurred due to the emplacement of Late Triassic granitic magma. An ENE-trending sinistral shear zone developed and shows the deformation characteristics of shallow ductile crust, reflecting apparent thinning and decratonization of the North China Craton continental crust (Liang et al., 2015a, 2015b).

The mullions occur on the contact of the fine-grained biotite adamellite and the coarse-grained granitic gneisses. The contact boundary has a lobate-cuspate shape. The convex direction of mullions indicates that the biotite adamellite is less competent than the granitic gneisses (Fig. 2a–d). Where the contacts are perpendicular to the foliation, the mullions show a symmetric shape. Where the contact has a moderate intersection angle with foliations, the mullions are generally an asymmetric shape (Fig. 2e). On those contacts parallel to the foliation, no mullions occur.

3. The geometry model and measurement of mullions

3.1. Geometry model and parameters

A geometrical model is built to describe the geometry of mullions quantitatively (Fig. 3). Therefore, the shape of mullions can be classified and their growth is analyzed by using a series of parameters as presented in Table 1. The arc length L_{arc}, width W_i and amplitude H of each lobe are describing the size and shape growth of mullions under the assumption of shortening parallel to the interface. The length of the tangent line on the hinge L_c describes the roundness or sharpness of the hinge area. The inter-angle θ between the Tangent line cross the cusp point and the growth direction of lobes describes the tightness and evolution of the cusps. In fact, the geometric shape of mullions could possibly be asymmetric because of the random initial disturbances, so these parameters have been defined on a half lobe and its neighboring half cusp. The measurement of these geometry parameters will be examined on the maximum shortening direction, generally the direction perpendicular to the foliations or axial surface of folds.

3.2. Measurement results

In the study area, 25 points of mullions in four locations are measured in the field (Fig. 2 and Table 2). The minimum half lobe width of these mullions is about 1 cm, and the maximum is more than 30 cm. The amplitude ranges from 1 to 40 cm. The dominant ratios of the amplitude and half width of lobes are between 1.0 and 2.0, and the maximum ratio is up to 4.36. Field measurements

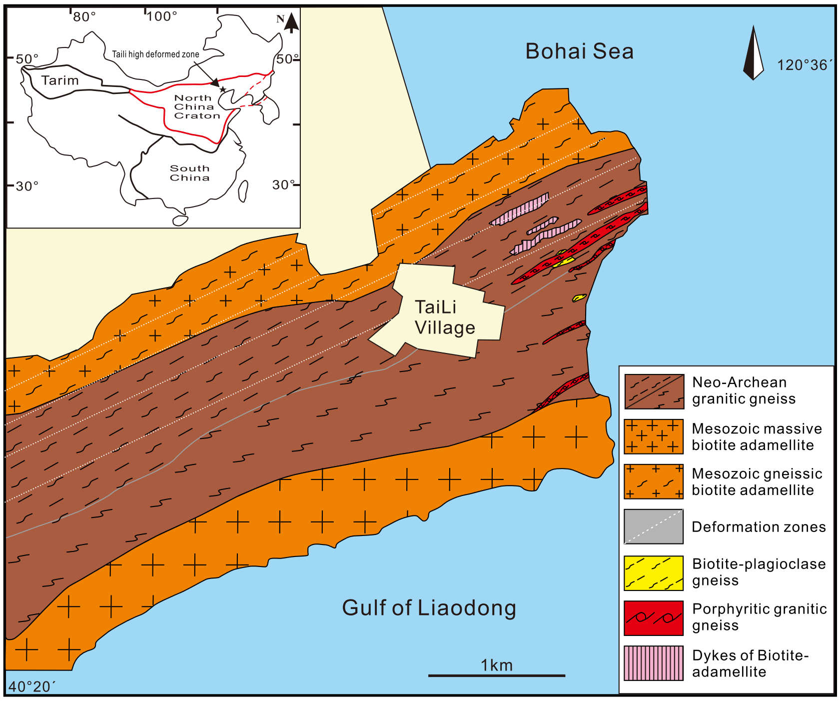

Fig. 1. Tectonic setting of Taili high deformed zone (from Liang et al., 2015a).

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