Pull-apart micro-structures and associated passive folds

Soumyajit Mukherjee[1] Rupam Chakraborty[2]
Indian Institute of Technology Roorkee, Roorkee-247667, Uttarakhand, INDIA

ABSTRACT

Due to tectonic forces in the grain-scales, minerals in clastic rocks get broken and/or rotated giving rise to pull-apart micro-structures. The matrix foliation moves into the offset generating passive folds. Assuming the matrix to be incompressible Newtonian viscous fluid, the passive folds are numerically analyzed in this work.

INTRODUCTION

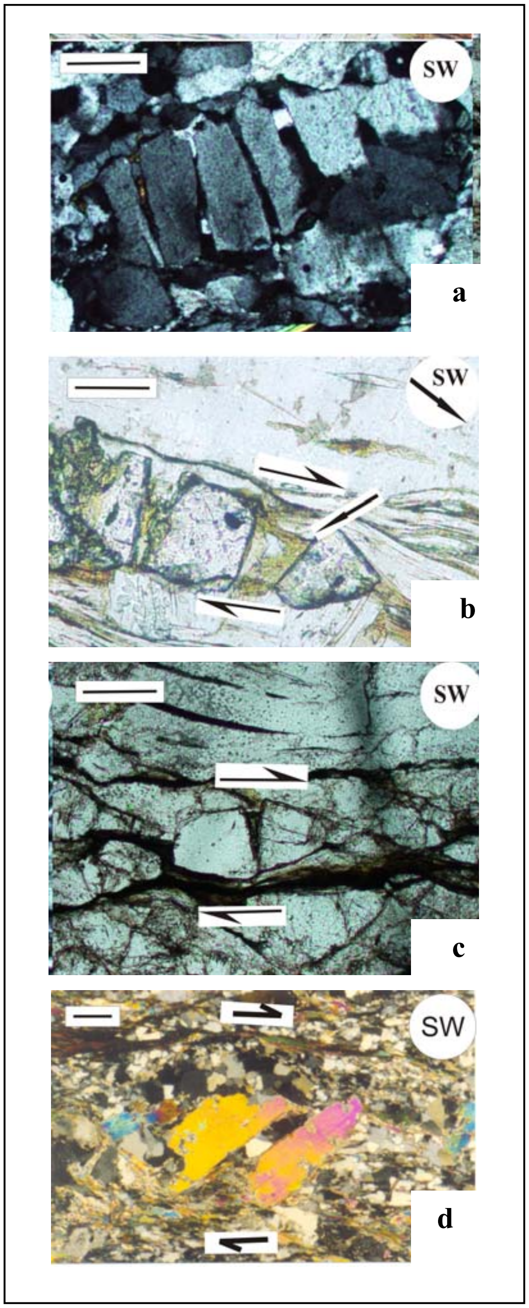
Clastic rocks are inhomogeneous, granular and are defined by a single or different species of mineral(s). Due to macro/micro-tectonic forces acting at small/grain scales, these minerals might get broken, separated and/or rotated. Such intra-granular brittle fracturing and rigid body rotation of porphyroclasts are called as the pull-apart micro-structures. The fragments occur within the mechanically heterogeneous intensely sheared matrix. Careful analyses of these structures can provide a range of kinematic information about the deformation/rheology of the rock/mineral. In pull-apart micro-structures, mineral grains of different shapes undergo brittle fracturing, offset with respect to each other and/or rigid body rotation. The gaps created by these structures suck the matrix inside them, giving rise to *passive folds*. Pull-apart structures are not very abundant in micro-scales, but have the potential to be used as reliable kinematic indicators. Graphical analyses of passive folds, in this work, lead to their geometric classification. Assuming the matrix to be incompressible Newtonian viscous fluid, continuum model for the generation of passive folds are derived. The derivation is based on hydrodynamic theories, and highlights the controls of physical- and kinematic factors on their progressive development. The derivation is applicable for modeling the heterogeneous flow for (i) both equant- and inequant shaped inclusions, and (ii) simple shear deformation of the matrix.

NATURAL OBSERVATIONS

A variety of pull-apart micro-structure occurs in the mylonitized gneisses of the Zanskar Shear Zone (ZSZ), Western Indian Himalaya. The ZSZ is the tectonic boundary between the Higher Himalayan Crystallines in the south and the Tethyan Sedimentary Zone in the north.

The studied thin-sections are perpendicular to the north-easterly dipping main foliation and parallel to the north-easterly plunging stretching lineations. High-grade and rigid minerals viz. garnet, staurolite, and also alkali feldspar and muscovite occur as porphyroclasts floating in fine grained matrix of quartz, mica and feldspar. The matrix materials are presumably less rigid.

The Type-1 pull-aparts, characterised by parallelism between the fractured walls of the separated fragments, is not indicative of any shear sense (Figs. 1a, -d). In contrast, the 'V'-pull-apart micro-structure with non-parallel gaps between separated fragments is indicative of the brittle shear sense (Figs. 1b, -e).



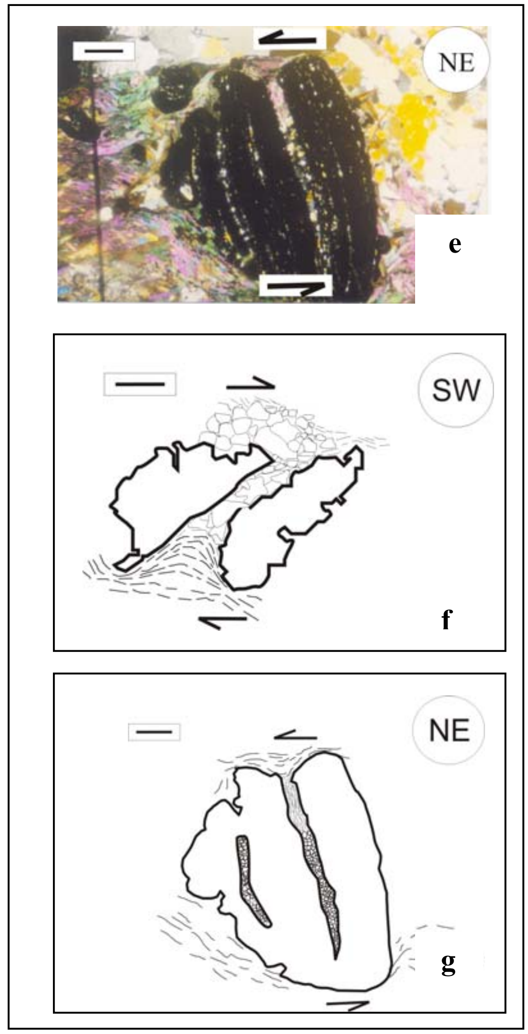


Figure 1: Natural examples of V pull-apart indicating top-to-SW sense of brittle shear, & parallel pull aparts indicating brittle extension parallel to the main foliation. From the Zanskar Shear Zone, western Indian Himalaya. (a) parallel type, alkali feldspar; (b) V type, chlorite passive folded at the gap, shown by arrow; (c) V type, originally lenticular muscovite fish; (d) parallel type, muscovite,, rigid body rotation in response to brittle fracturing took place; (e) V type, garnet. (f) & (g) are line sketches of (d) & (e), respectively. (a), (d) & (e) in cross-polarized light. (b) &

(c) in plane polarized light. Scale bar in each photograph: 0.8 mm.

GEOMETRY OF PASSIVE FOLDS

The amplitudes of the passive folds diminish away from the separation zone (the 'gap'). Twenty points of the parameters- T'_α, t'_α and α, as defined in Ramsay[1], of these passive folds are plotted in Figs. 2a & -b. These data indicate the passive folds to be 'Class-3'.

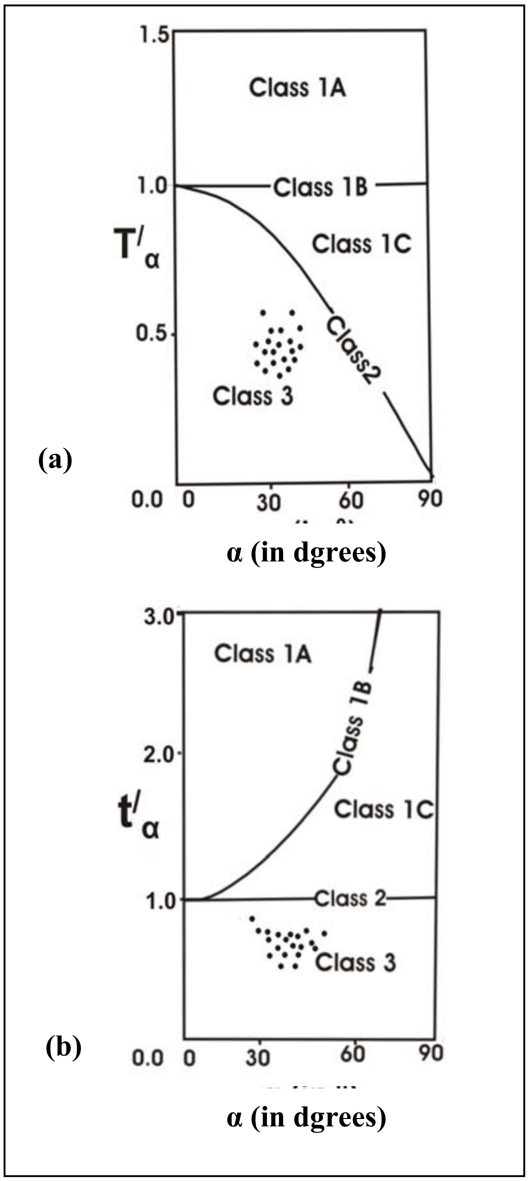


Figure 2: Plot of passive folds in Ramsay's[1] diagram.

NUMERICAL ANALYSES

Referring to Fig. 3, let ABEF and CDEB are the cross-sections of adjacent segments of originally single rigid brittle object within infinitely extended Newtonian viscous medium of density ρ. Let the fragments have infinite width in the Z-direction. This justifies the assumption of plane flow. Under the progressive simple shear condition, the viscous flow of the matrix exerts shear stresses over the object surfaces. The rotation of the smaller- and the larger fragments having angular velocities ω_1 and ω_2, respectively, in effect sucks the matrix inside the gap.

We now derive the radial- and the tangential velocity components useful to determine the kinematics of the generation of passive fold associated with different kinds of pull-aparts.

The velocity field is defined in the (r,φ,z) cylindrical co-ordinate (Fig. 4), as

$$\vec{u}(r,\varphi) = u_r(r,\varphi)\vec{e}_r + u_\varphi(r,\varphi)\vec{e}_\varphi \quad (1)$$

whose radial component, with the unknown function: f(r), is

$$u_r(r,\varphi) = f(r)\cos(\frac{\pi}{\theta}\varphi) \quad (2)$$

The velocity of the bottom- and the upper fragments, respectively, are

$$\vec{u}_r(r) = \omega_1 r\vec{e}_\varphi \quad (3)$$

$$\vec{u}_r(r) = -\omega_2 r\vec{e}_\varphi \quad (4)$$

The continuity equation of integral form is given by

$$\iiint_{(V)} \frac{\partial \rho}{\partial t} dV = -\iint_{(S)} \rho \vec{u}.\vec{n} dS \quad (5)$$

The integral is carried out over the sketched control volume (Fig. 4 and its caption), which also coincides with the material volume. The movement of the fragment causes the fluid to move into the control volume via surfaces S_1, S_2 and S_3. The left hand side of (5) can be written as

$$\iiint_{(V)} \frac{\partial \rho}{\partial t} dV = 0 \quad (6)$$

since ρ is constant.

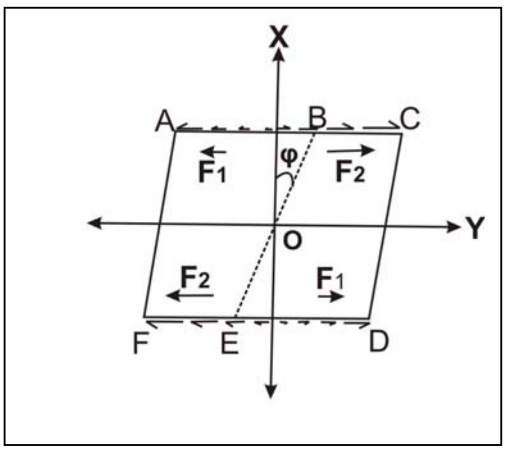


Figure 3: (a) Geometrical representation of two segments of an object in a co-ordinate frame x, y; the arrows on- and inside the boundaries indicate the shear stresses exerted by a viscous flow and the resultant forces on the segments, respectively. Here the pulling force F_u=2F_1 and the coupling force F_r =(F_u-F_1); (b) Brittle fracturing followed by rigid body rotation under progressive-deformation.

The surface integral is carried out over the entire control volume

$$\iint_{(S_1)} \rho \vec{u}.\vec{n}_1 dS + \iint_{(S_2)} \rho \vec{u}.\vec{n}_2 dS + \iint_{(S_3)} \rho \vec{u}.\vec{n}_3 dS = 0 \quad (7)$$

The kinematic boundary condition requires that the normal velocity component $\vec{u}.\vec{n}$ of the flow at surface S_1 is equal to the normal component of the plate velocity. This requirement leads to, from Eq. (7),

$$\int_0^b \int_0^{\theta/2} -\omega_1 r dr dz - \int_0^b \int_0^{\theta/2} f(r) \cos(\frac{\pi}{\theta}\varphi) + \int_0^b \int_0^{\theta/2} -\omega_2 r dr dz = 0 \quad (8)$$

In Eq. (8), the integration $\int_0^b$ represents the extension in Z-direction. The integral is assumed to be infinity and can be cancelled out. Thus Eq. (8) leads to,

$$-\frac{1}{2}(\omega_1 + \omega_2) r^2 - r f(r) \frac{\pi}{\theta} [\sin(\frac{\pi}{\theta}\varphi)]_0^{\theta/2} = 0$$

or $\quad f(r) = -\frac{\pi}{2\theta}(\omega_1 + \omega_2) r$

From Eqs. (2) & (8), the radial velocity component is given by

$$u_r(r,\varphi) = -\frac{\pi}{2\theta}(\omega_1 + \omega_2) r \cos(\frac{\pi}{\theta}\varphi) \quad (9)$$

Using the differential form of continuity-equation, we calculate $u_\varphi(r,\varphi)$, with the boundary condition

$$\varphi = \pm \frac{\theta}{2}$$

We know

$$\frac{\partial (r u_r)}{\partial r} + \frac{\partial u_\varphi}{\partial \varphi} = 0 \quad (10)$$

From Eqs. (9) and –(10):

$$\frac{\partial u_\varphi}{\partial \varphi} = -\frac{\pi}{\theta}(\omega_1 + \omega_2) \cos(\frac{\pi}{\theta}\varphi) \quad (11)$$

Integrating (11):

$$u_{\varphi}(r,\varphi) = -(\omega_1 + \omega_2) r \sin(\frac{\pi}{\theta}\varphi) + C(r) \qquad (12)$$

Now, considering the flow to be symmetric with respect to the X-axis,

$$u_{\varphi}(r,\varphi) = -u_{\varphi}(r,-\varphi) \qquad (13)$$

From Eqs. (12) &-(13),

$$C(r) = 0$$

Using this in Eq. (12), the tangential velocity component is given by:

$$u_{\varphi}(r,\varphi) = -(\omega_1 + \omega_2) r \sin(\frac{\pi}{\theta}\varphi)$$

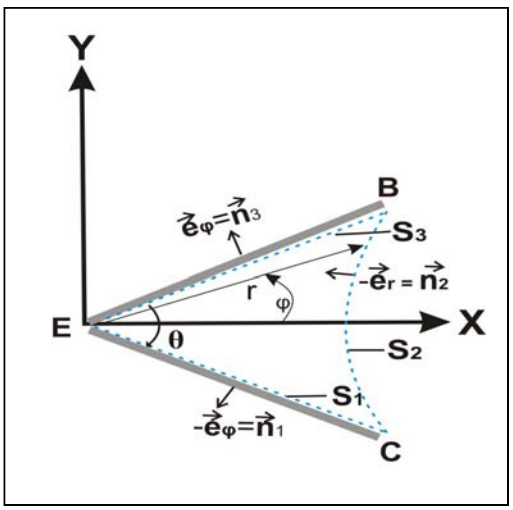


Figure 4: Geometric representation of adjacent segments of an object in co-ordinate frame x, y. The control volume is defined by the dotted arc and the lines EB and EC. Relative rotation of smaller fragment CDFE with respect to larger fragment ABEG, with respect to X-axis, generates the pull-apart and the separation.

CONCLUSIONS

(1) We provide natural examples of pull-apart micro-structures from the oriented thin-sections of the Zanskar Shear Zone, western Indian Himalaya. (2) The asymmetry of the 'V' pull-aparts relative to primary shear plain gives top-to-SW sense of shearing. (3) The passive folds belong to the Class-3 of Ramsay[1]. (4) The genesis of the passive folds depends on (i) the aspect ratio of the brittle porphyrocalst before fracturing, and (ii) the rigid body rotation of the grain fragments. (5) The kinematics of the passive folds depends on the radial- and the tangential velocity components of inflow of the matrix at the separation/gap.

ACKNOWLEDGEMENTS

SM acknowledges a 2005-2006 "Guest Scholarship" awarded by the "Swedish Institute" to carry out this work in the Hans Ramberg Tectonic Lab, Uppsala University.

REFERENCES

1. Ramsay, J.G. (1967), "*Folding and Fracturing of Rocks*". McGraw-Hil, New York.