Slip localization within a heterogeneous fault-zone
Earthquakes and reactivation along the Pretorius fault-zone, Tautona mine, South Africa (NELSAM)

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Problem

Many fault-zones display complex assemblages of fault-rocks (gouge, mylonite, or cataclasite) that bound blocks of damaged and intact host-rock. This structure of anamolous, cross-cutting segments may develop into a mature fault-zone during repeated episodes of faulting. The heterogeneous assembly of different rock types that exists within fault-zones is likely to control the fault evolution under various stress states. We analyze here mechanisms of heterogeneous fault zones. The analysis is presented in three steps:

1. Field observations of the structure of a heterogeneous fault-zone (the Pretorius fault) and the earthquake rupture on it.
2. Rock mechanics experiments of the fault-rocks and the host rock.
3. Finite element analysis of shear localization in this fault-zone.

Field observation

The Pretorius fault

The study is based on observations of reactivation of the Pretorius fault, which is one of the major faults in the Western Deep region, Witwatersrand basin, South Africa. We studied this fault in the Tautona mine at depth of 3-6 km as part of the NELSAM project (Natural Earthquake Laboratory in South African Mines).

The Pretorius fault is about 10 km long and 20–30 m wide, with a vertical throw up to 60 m, and it was not active during the last 2.5 Ga. The fault-zone contains multiple segments with cataclasite that undergo low-grade metamorphism. The cataclasite is similar in composition to the host rock, but of finer grain size. The fault segments form a complex anamolous pattern of intersecting, quasi-planar surfaces, in between these surfaces the fault-zone consists of host-quartz (Figure 1).

Fault reactivation

The NE2 of December 12, 2004, reactivated three of four quasi-planar segments of the Pretorius fault within the NELSAM area (Figure 1). We mapped the rupture to 25 m horizontally and 6 m vertically in a few cross-cutting tunnels. Displacement of man-made tunnels (rock bolts) revealed normal-dextral slip up to 25 mm.

Rupture surface

The rupture is characterized by zones of fresh, white gouge (rock powder) that are typically located 10 m thick zones along discontinuously along the contacts between the quartzite-host rock and the ancient cataclasite (Figure 2).

The understanding of the mechanism that is responsible for the slip localization along the contacts within the fault-zone, will contribute to the understanding of fault reactivation processes in general.

Rock mechanics experiments

Experimental condition

The mechanical experiments were conducted on 23 samples from within the fault-zone, collected in continuous coring drilling along the Pretorius fault. The samples consist of quartzite from within the fault-zone (damaged host rock) and samples of the cataclasite (Figure 3). All experiments were conducted under dry, room temperature conditions with 0-200 MPa confining pressures, and shearing rates of 0.5-10^-7.

Results: Brittle-plastic vs. Brittle-elastic rheology

The host quartzite and the cataclasite display distinct mechanical behavior (Figure 4). a. The quartzite is twice as strong as the cataclasite.

b. The quartzite is severely damaged (Figure 5), showing significant plastic deformation and strain hardening. We refer to this behavior as Brittle-plastic material.

c. The cataclasite is localized along the cross-cutting fault with no significant offset damage. The cataclasite is a Brittle-elastic material with no strain hardening.

The heterogeneity of the Pretorius fault-zone is reflected in these contrasts between the mechanical properties of both rheologies (Table 1).

FEM result summary

The FEM models show:

1. The shear stress inside the inclusion is significantly lower than the shear strain in the surrounding medium (Fig. 6a, 7a).

2. The profiles (Fig. 6b, 7b) show an abrupt increase of the shear stress at the contact between the inclusion and the medium.

3. The high intensity of the equivalent plastic shear strain in the medium indicates that the host rock is in a stage of failure.

Discussion:

Strain gradient, slip localization, and reactivation mechanism

The steep gradient of the shear strain at the contact of the inclusion reflects the contrasts of mechanical properties between the fault-rock and the host rock. This steep gradient forms a likely site for slip localization (e.g., Fleen and Hufnagel, 1993). A Phenomenological Theory for Stratigraphic Grain Stress in Plasticy (the plastic shear strain shows an increase in the shear stress, suggesting that the gradient in shear stress is the result of the plastic behavior of the medium. Thus, the model suggest that the plastic behavior of a damaged host rock in a heterogeneous fault zone may result in high gradients of shear strain parallel to the contact of the elastic, brittle fault-rock, forming the seed for strain and slip localization along the contact.

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