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# Fault mirrors along carbonate faults: Formation and destruction during shear experiments

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ABSTRACT

Glossy, light reflective surfaces are commonly exposed in carbonate fault-zones. It was suggested that such surfaces, recently termed Fault Mirrors (FMs), form during seismic slip. Ultramicroscopic analyses indicate that FMs are highly smooth and composed of a cohesive thin layer of nano-size grains. We explore here mechanisms of formation and destruction of FMs by shear experiments that were conducted on three types of limestone which were sheared at wide range of slip-velocities of $v = 0.001$–$0.63$ m/s, and normal stress up to 1.57 MPa. The experiments showed that FMs started to develop as local patches when the slip velocity exceeded a critical value of 0.07 m/s. The area coverage by FM patches increases systematically with increasing velocity, reaching in a few cases ∼100% coverage. The measured quasi-steady-state friction coefficient, $\mu_{ss}$, was inversely correlated with the FM coverage: $\mu_{ss} \sim 0.8$ for no-FM, at $v < 0.07$ m/s, and $\mu_{ss} \sim 0.4$ for 50% FM coverage at $v \sim 0.6$ m/s. Further, in a series of slip-velocity alternation between low and high values, the FMs which formed at a high-velocity stage were destroyed during a subsequent low-velocity stage. Our analyses of the experimental thermal conditions and ultramicroscopy imaging of the FMs suggest that the FMs form by sintering of gouge nanograins during shear. We propose that formation/destruction of FMs in high/low slip-velocity reflects a competition between brittle and ductile processes: FMs form in a ductile mode, and are destroyed by brittle wear. Shear heating during high velocity leads to ductile deformation and sintering so that FM construction rate exceeds brittle FM destruction rate. Based on our results, we suggest that, at least for shallow faults, the presence of extensive FM coverage along natural carbonate faults indicates that the fault segment slipped at seismic velocities and experienced dynamic weakening.

## 1. Introduction

Smooth, glossy, light reflective surfaces, are commonly observed on carbonate fault-zones in the field and laboratory shear experiments (Boneh et al., 2013; Chen et al., 2013; Fondriest et al., 2013; Han et al., 2010; Siman-Tov et al., 2013; Smith et al., 2013; Tisato et al., 2012; Verberne et al., 2013). These surfaces, recently termed Fault Mirrors (FMs), are composed of tightly packed nano-size grains (Siman-Tov et al., 2013; Tisato et al., 2012) or polygonized surfaces (Smith et al., 2013), they are optically smooth and their measured roughness is lower than 100 nm at scales <550 nm (Siman-Tov et al., 2013). FMs were experimentally observed to form under high slip rates (Smith et al., 2013), and their evolution was also affected by slip-distance and the magnitude of the normal stress (Fondriest et al., 2013; Proctor et al., 2014). The observation of FMs on carbonate faults was recently proposed as a potentially promising indicator for paleo-seismic slip (Fondriest et al., 2013; Siman-Tov et al., 2013; Smith et al., 2013). The present objective is to experimentally test the hypothesis that FMs in carbonates may serve as seismic indicators.

We present here results from tens of rotary shear experiments using three types of limestone samples, at a wide range of slip velocities. We characterize the conditions for creation and destruction of FMs, and compare the experimental results to field observations. The analysis includes: (1) Shear of carbonate experimental faults; (2) Image processing of the experimental fault surfaces to quantify the area coverage by FMs; (3) Numerical modeling of the thermal evolution within the sheared fault-zone; and (4) Characterization of the nano-scale features on the slip surfaces by ultramicroscopy tools (high resolution scanning electron microscopy (HR-SEM), and high resolution transmission electron microscopy

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(HR-TEM). Based on the synthesis of these analyses, we propose a conceptual model for the formation of FMs and discuss their connection to fault dynamic weakening.

## 2. Methods

### 2.1. Experimental set-up

The experiments were conducted with the rotary shear apparatus at Oklahoma University (ROGA, apparatus details in Boneh et al., 2013; Reches and Lockner, 2010). This system is capable of applying normal stress up to 35 MPa, slip velocities of 0.001 to 2 m/s, and un-limited slip displacement. The experimental faults are built of two cylindrical blocks (Fig. S1). The lower, rotating, block is a solid, flat cylinder 101.6 mm in diameter. The upper, stationary, block is a hollow cylinder with dimensions of either 51.5 mm and 75.8 mm as inner and outer diameters, respectively, or 51.5 mm and 100.6 mm, respectively (Table S1). Both blocks were ground flat, then roughened with #600 SiC grit, and dried for ∼24 h at 100 °C.

We ran 51 shear tests with continuous monitoring (up to 1.2 kHz) of records of normal load, shear load, slip velocity, sample temperature, and change in closure/opening normal to the fault. This last measurement, of the system's dilation and compaction, mainly reflects the surface wear (Boneh et al., 2014; Reches and Lockner, 2010). Loading conditions were: slip-velocities of $v = 0.001$–$0.63$ m/s, total slip distance 0.0075–8.3 m, and normal stress $\sigma_{\mathrm{n}} = 0.47$–$1.57$ MPa. Low normal stresses were used to reduce the failure of the thin, hollow cylinder of the stationary block (Fig. S1), however, running at this normal stress does not limit the implications of the results as discussed extensively in the Discussion (see Section 4.4). All experiments were run at room conditions.

The experiments consisted of three velocity profile types: Constant velocity, stepped velocity, and triangular shaped velocity profiles. For the constant velocity type, velocity was accelerated during ∼1 s to the selected value, slipped for a given period and then decelerated to a complete stop. For the stepped velocity type, each constant velocity level (up to 5 steps) was ended with abrupt velocity jump to the next higher velocity (see Chen et al., 2013, Fig. 2B). Velocity steps went from low to high velocities. For the triangular velocity profile, a constant acceleration was imposed ($0.007$–$0.036$ m/s$^2$) until a peak velocity was reached, and then a constant deceleration was imposed, until a complete stop was attained.

The experimental faults were made of three carbonate rocks (Table S1). The first type is Kfar Giladi (KG) limestone which is an Eocene Bar Kokhba formation from northern Israel. It is a shelf facies comprised mostly of bio-micritic limestone with nummulites. Samples of KG limestone were collected from a quarry that is cut by a series of active faults at the margins of the Dead-Sea transform (Levi and Weinberger, 2011; Nuriel et al., 2012a, 2012b; Weinberger et al., 2009). The discovery and analysis of FM surfaces in this quarry by Siman-Tov et al. (2013) motivated the present experimental study. The second type of limestone is Brown Lueders (BL) (commercial name), a fine-grained Permian limestone from Lueders, Texas. It is macroscopically homogeneous and isotropic bio-micritic rock, mostly comprised of calcite (Heard et al., 1972). The third type of limestone is Dover Gray (DG) (commercial name), a crystalline limestone with fossil fragments, quarried by Higgings Stone, Kansas. The Dover light gray limestone defined as a formation within the Carboniferous Wabaunsee group (Moore, 1936).

### 2.2. Analytical techniques

Further analyses were conducted on eight experiments run on DG limestone (#2055–2062). These experiments were run at varies constant velocities ranging between 0.003–0.6 m/s, and under the same conditions of slip distance ($3.3 \pm 0.3$ m) and normal stress ($1.4 \pm 0.2$ MPa) (Table S1). After each of the eight runs, the experimental fault was opened, its surface was photographed, the amount of FM coverage was calculated and the average temperature on the slip surface was modeled as described below. For all other experiments presented here, we report only whether they were opened after the experiment, and if yes, whether FMs were observed to cover the slip surface area (Table S1).

#### 2.2.1. Evaluating fault mirror coverage

During high slip velocity experiments the sheared surfaces developed a partial cover of glossy, mirror patches (Fig. 7 in Boneh et al., 2013). The glossy patches are easily recognized by their darker appearance relative to the surrounding gouge powder (polygons outlined in blue in Fig. S2). Following Siman-Tov et al. (2013), we term these glossy patches Fault Mirrors (FMs). The area covered by FMs was calculated by digitally mapping the patches on post-experiment photographs of the lower rotated samples, and presented as its fraction of the experimental fault area.

#### 2.2.2. Temperature measurements and modeling

Temperature was measured by two thermocouples embedded 90° apart along the ring center in the upper, stationary block (Fig. S1A). Their distance from the fault surface was a few millimeters; e.g., 5.6 and 6.1 mm for DG limestone experiments (#2050–2062). A 3D heat conduction model, using COMSOL Multiphysics software, was then used to calculate the spatial and temporal temperature distribution on the fault surface and within the solid blocks, with the actual geometry of the experimental sample. Model results were calibrated with respect to the experimental thermocouples record. It is assumed that (1) all mechanical work is converted into heat (Rice, 2006); (2) conduction is the only mechanism of heat transfer within the solid; and (3) the rate of frictional heating equals the experimental mechanical power density (PD) having units of W/m$^2$:

$$\mathrm{PD} = \tau \cdot v \tag{1}$$

PD is calculated from the measured shear stress, $\tau$, and slip velocity, $v$, and it is uniformly distributed on the slip area. The heat source was modeled as a 2D planar source positioned in the middle of a 100 μm thick gouge layer, bound by two solid rock blocks. This structure simulates the observed post-shear structure of the high-velocity experiments that displayed surfaces within <100 μm thick gouge layer (see Section 3.2). For the low slip velocity experiments, where no FMs were observed, we also tested a volumetric heat source that corresponds to linearly distributed shear within a 100 μm gouge layer. Results predict no noticeable difference at the thermocouple location, between the localized versus distributed heat sources; thus, all results are presented using planar source heat supply as boundary condition. We used constant thermal properties for the gouge layer and temperature-dependent specific heat capacity and coefficients of thermal conductivity for the solid limestone (for more details see Supplementary Material (SM) text and Table S2).

## 3. Results

### 3.1. Velocity dependence of frictional strength

We conducted 51 shear experiments of single and stepped velocity. From experimental friction-distance curves (e.g. Fig. 1C), we determined 96 values of friction coefficient during the middle stage of the constant velocity part of the experiment, which typically display a nearly steady state value of friction ($\mu_{\mathrm{ss}}$). We refer to this experimental stage as 'quasi-steady-state' as the slip