EVOLUTION OF HOST-ROCK DEFORMATION AND DAMAGED ZONES AROUND INTERACTING EN ECHELON DYKE SEGMENTS

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INTRODUCTION

Dykes producing their own fractures are expected to propagate more or less perpendicular to the least compressive stress in the host rock (mode I loading, Fig. 1a). Pure mode I loading produces in-plane propagation and planar dykes, but field observations demonstrate that dykes are commonly segmented, indicating that some shear stresses are resolved on the dyke planes (Delaney and Pollard, 1981). The shear loading may be applied perpendicular to the dyke periphery (mode II loading, Fig. 1b), or parallel to the dyke periphery (mode III loading, Fig. 1c) (Pollard, 1987). Theory postulates that even a minor component of mode II or mode III loading will produce out-of-plane propagation and segmentation (Erdogen and Sih, 1963). Thus, en echelon dyke segments have been interpreted as breakdown segments of a planar parent dyke that propagates under mixed-mode loading (Pollard et al., 1982). Features of en echelon dyke segments include the morphology of the breakdown zone (Kattenhorn and Watkeys 1995), geometry of the segments and their connection (Pollard et al., 1982; Olson and Pollard, 1989; Thomas and Pollard, 1993), overall propagation direction and local propagation directions (Baer, 1991, 1995).

Loading conditions are also responsible for the pattern and style of secondary fractures associated with a propagating dyke. Parallel fractures along dyke walls and beyond dyke tips are inferred to initiate under mode I loading of the dyke.The fractures may consist of closely spaced dyke-parallel joints (Delaney et al., 1986; Hoek, 1995), dyke-parallel deformation bands (Weinberger et al., 1995), and mineralized fractures (Rogers and Bird, 1987). In the present study, the formation of en echelon dyke segments and associated secondary fractures under mix-mode loading are examined. We evaluate the significance of the secondary fractures as paleostress indicators by simulating host-rock deformation around mechanically interacting dyke segments under different states of stress. A field example from Makhtesh Ramon is presented and discussed. Preliminary analysis suggests that the Ramon dyke studied was intruded under conditions of a minor remote differential stress.

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THE EN ECHELON DYKE SEGMENTS IN MAKHTESH RAMON

The Makhtesh Ramon dykes propagated generally in subhorizontal directions up to a distance of 15 km from their source (Baer and Reches, 1991). In the Inmar Formation sandstone dyke segments locally propagated in oblique directions parallel to long dyke steps. "Fingers" (elongated ridges and rills that are molded in the host quartzitic surface (Baer, 1991) and the long steps are generally subparallel. However, close to dyke steps, always at their southern sides, the fingers change their orientation significantly and locally become perpendicular to the adjecent step (Baer, 1991). In terms of linear-elastic-fracture-mechanics (LEFM) segmentation and the associate change in the propagation direction occurred under mixed-mode loading conditions of the parent crack that precedes the magma. The parent crack propagated both horizontally and vertically from the inferred magma source (Fig. 2), and incipient cracks deviated from its top periphery when shear was resolved on its plane. Locally, adjacent incipient cracks propagated laterally toward each other (or at least one segment toward the adjacent segment) and interacted until they linked and subsequently dilated as a continuous segmented dyke.

DEFORMATION AROUND ECHELON DYKE SEGMENTS

In this paper we present and discuss one typical continuous segmented dyke (Fig. 3). The dyke consists of many prominent left-stepping segments. The segments are typically several meters wide, 0.2 m thick, and offset by 0.1 m. In plan view, the step (connector) between two segments forms a curved line (Fig. 3), which is the trace of a wavy curved surface dipping about 55°.

The associated deformation consists of shear features, also termed "deformation bands" (Aydin, 1978; Weinberger et al., 1995) which consist of roughly planar, thin lamellae of fine crushed quartz grains with

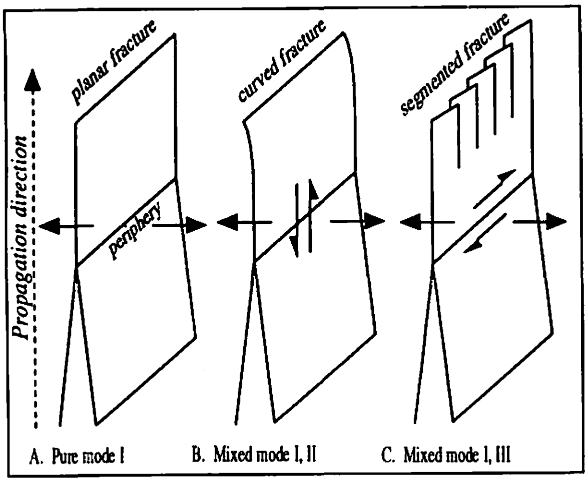

Figure 1. Schematic illustration of fracture propagation paths under mixed-mode loading (see text).

distinct porosity reduction relative to the host rock. The deformation bands are observed on either side of the dyke segments. They are straight or slightly curved (in plan view), up to 4 m long, and are generally asymmetric about the dyke plane.Typically, a straight deformation band merges with and continues beyond the segment wall, oriented parallel to the general trend of the segment (Fig. 3). The host-rock deformation as manifested by the deformation bands may be enclosed within lobe-shape zones of distributed macroscopic deformation (Fig. 3).

SIMULATING ECHELON DYKE SEGMENTS

Background

Mechanical analyses of fluid-driven cracks generally treated the host-rock as a linear elastic material (e.g., Pollard, 1987). The cracks are idealized as sharp slits, introducing a singularity at the crack-tip in the LEFM solutions. However, natural materials cannot withstand infinite stresses and instead deform inelastically around the crack tip. Experiments and field observations show a region of inelastic deformation, or process zone, on variable scales (Rubin, 1995), that invalidate the LEFM assumption that the size of this region approaches zero.

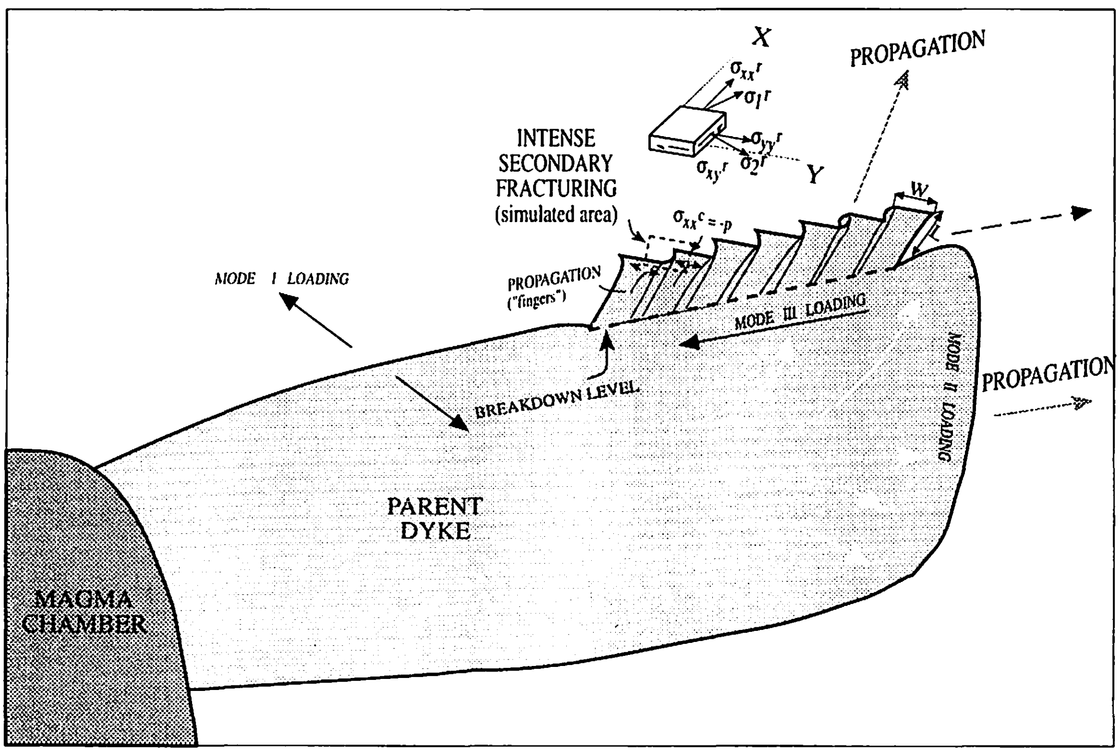

Figure 2. An idealized Ramon dyke propagating simultaneously upward and laterally from the magma chamber. The parent dyke is subjected to mode I loading and horizontal shear. En echelon curves form in mixed-mode I+III loading at the top of the parent crack. Local propagation directions within the segments as inferred from "fingers" are indicated by solid arrows; possible opposite propagation directions are indicated by broken-line arrows (not observed). x y are axes in cross section and the stress components are shown (tensile stress reckoned positive).

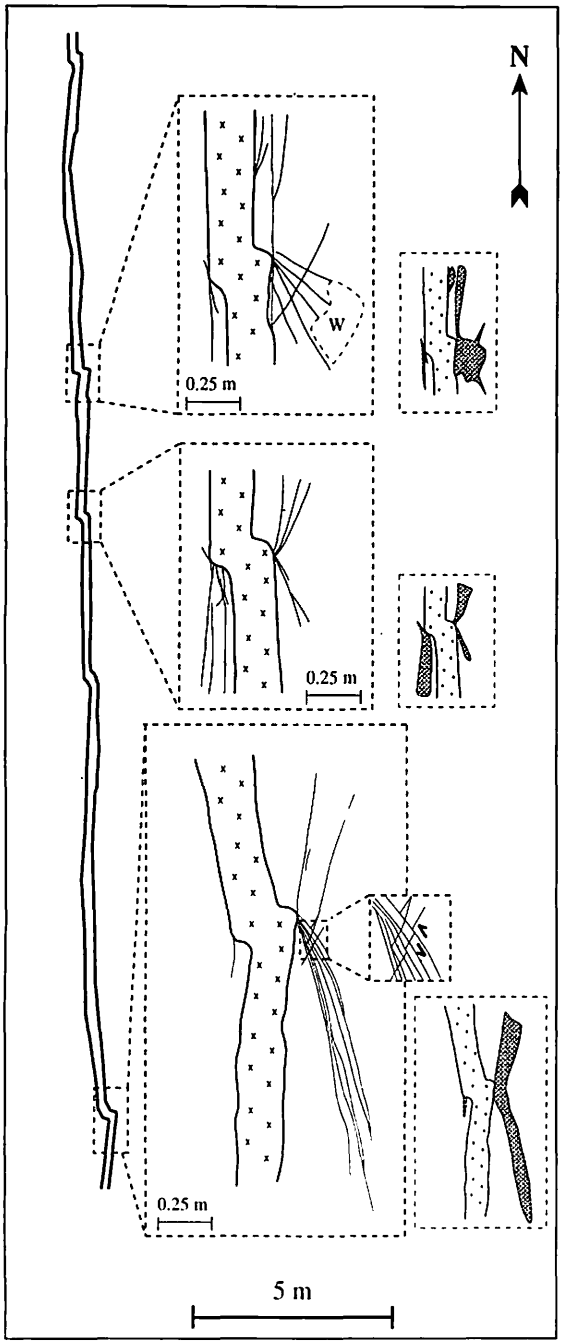

Figure 3. Map of continuous left-stepped dyke and deformation bands associated with its steps, Makhtesh Ramon, Israel. The deformed host-rock is enclosed within lobe-shaped zones (gray regions) of intense macroscopic deformation.

In order to avoid the crack-tip singularity introduced by the LEFM approach, and account for the non-linearity response of the material, we have adopted a damage rheology model (Lyakhovsky and Myansnikov, 1984; Lyakhovsky et al., 1993). This model ensures finite stress values at the crack tip, and a finite strength to the host-rock. The model permits interaction of the near-field inelastic deformation with the crack-tip via its influence on the stress field. The simulation of magma intrusion into a non-linear host-rock is made under the assumption that the host-rock is initially crack-free and behaves as a linear Hookean material (Agnon and Lyakhovsky, 1995). Fluid-filled cracks are embedded within the material and remote loading is applied, initiating microcracking along favorable planes. The distribution of microcracking is controlled by damage, which is accounted for by a scalar field. Once a critical damage value is exceeded, magma invades the cracked (damaged) host-rock and propagation occurs. Our model predicts the stress field and damage distribution in the material, without making assumptions about the geometry of the intrusion or of the process zone (see details in Agnon and Lyakhovsky 1995).

Boundary conditions for lateral growth of en echelon cracks

The boundary conditions are reduced to local and remote stresses within a cross section that is far above the breakdown level (Fig. 2). Thus, plane strain is assumed with remote stress components $\sigma_{xz}^r = \sigma_{yz}^r = 0$, and zero strain along the segments length. The internal pressure, p, is kept constant and the remote principal stresses σ_1^r and σ_2^r are applied in different magnitudes and different orientations with respect to the parent dyke plane (tensile stress reckoned positive). This assures that shear stresses are resolved along the parent dyke, and breakdown into segments is initiated.

Simulation results

In the first series of simulations we considered two offset segments subjected to uniform driving pressure and $\sigma_1^r = \sigma_2^r = 0$ (Fig. 4a,b,c). Initially, each segment was surrounded by a localized damage zone near its tip similar in shape and intensity to the damage zone near an isolated pressurized segment (Agnon and Lyakhovsky 1995). In-plane propagation of the segments was initiated when parts of the localized damage zones were filled with magma (Fig. 4b). A damage zone propagated ahead of each segment, and the damage zones converged until they merged. The distributed damage developed into several "lobes" of unequal size (Fig. 4). The long axis of the lobes was obliquely oriented to the plane of the segments. Propagation of the segments enlarged these lobes and the intensity of the damage increased. As soon

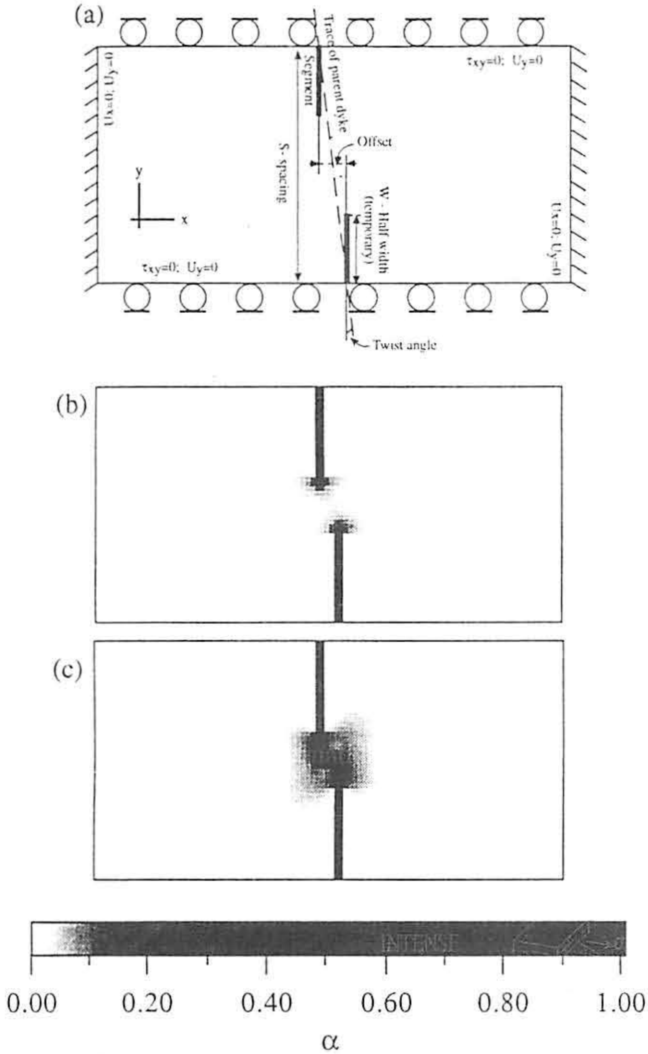

Figure 4. (a) Model geometry with boundary and initial conditions; (b-c) Two snapshots of damage distribution around propagating en echelon segments. Zero differential remote stress; internal pressure p = 5MPa; elastic moduli $\lambda = \mu$ = 20,000 MPa.

as the segments overlap their propagation was impeded, and damage culminated mostly in the a region between their tips. Finally, intruding magma connected both segments and contributed to the final stabilization of the segment configuration. For the mechanical variables that are used, the distribution of damage along each side of the segments is confined to a region smaller than half-width of the segments, and its shape resembles four lobes of unequal size (Fig. 4b,c).

In the second series of simulations the internal magma pressure was kept constant whereas the remote differential stress magnitudes (σ_1^r-σ_2^r) and orientation were changed systematically. Different distribution of

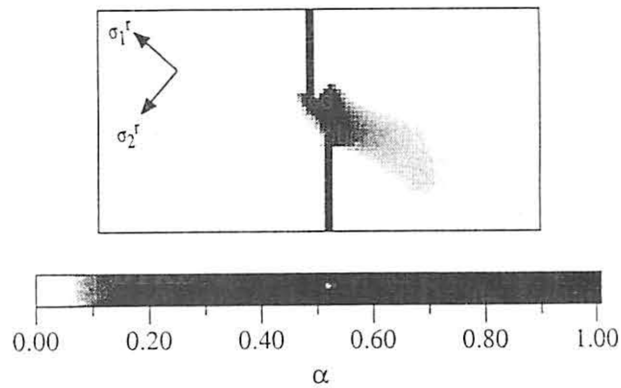

Figure 5. The damage distribution around propagating en echelon segments. σ_1^r-σ_2^r = 0.5; internal pressure p = 5 MPa at the lower segments and p = 1 MPa at the upper segment; elastic moduli $\lambda = \mu$ = 20,000 MPa (inset: σ_1^r oriented 45° with respect to the parent dyke).

damage developed under different loading condition. For example, for p=5 MPa at the lower segment, p=1 MPa at the upper segment, σ_1^r-σ_2^r = 0.5 and left-lateral shear displacement along the parent dyke plane (see Fig. 5:inset for orientation of the principal stresses), antisymmetric damage lobes obliquely oriented with respect to the planes of the segment were developed (Fig. 5).

DISCUSSION

The preliminary results of our simulations show that the shape of damage zones around the en echelon dyke segments is sensitive to the differential loading. We suggest that obliquity and distribution of damaged zones with respect to the segment planes may be used as a crude field criterion for estimating the differential remote stress conditions. A pronounced obliquity is more likely to develop under zero differential remote stress. On the other hand, a relatively wide deformation zone extending out and normal to the interaction zone between the segments (no obliquity of the damage zone) may be attributed to large differential remote stress.

In the case studied most of the deformation bands are enclosed along one (eastern) side of the dyke plane as lobe-shape zones (Fig. 3). According to our field criteria this corresponds to a near isotropic stress state. The lack of intense macroscopic deformation along the other side of the dyke plane is attributed to the obliquity of the principal stresses with respect to the parent crack, and to propagation of only one segment toward a stationary second segment (as applied in the simulation presented in Fig. 5).

We conclude that the studied dyke was intruded under minor differential remote stress. Our results are in agreement with the results of Baer and Reches (1991), that inferred minor differential stress during the emplacement of the Makhtesh Ramon dykes, based on the shape of the radial system.

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