Damage zones around en echelon dike segments in porous sandstone

Ram Weinberger,1,2 Vladimir Lyakhovsky,2 Gidon Baer,1 and Amotz Agnon2

Abstract. We investigate arrays of en echelon dike segments and their associated deformation in porous sandstone to infer the segmentation mechanism and the state of stress during dike emplacement. The en echelon arrays are interpreted as breakdown segments of planar parent dikes that propagated from greater depth under mixed-mode conditions. Typically, an array consists of either continuous nonoverlapping stepped segments (offset smaller than segment thickness) or overlapping connected segments (offset larger than segment thickness). The deformation associated with the nonoverlapping stepped segment arrays consists of newly documented fan-like patterns of deformation bands (lamellae of crushed detrital quartz grains), whereas the overlapping connected segment arrays consists of net-like patterns of deformation bands. Thus the patterns of deformation are related to offset geometry and are likely to be diagnostic of the states of stress. We simulated the stress and deformation fields around interacting breakdown segments by applying a continuum damage mechanics model. The simulation results mainly illustrate the stress dependence of the damage distribution and the sensitivity of the damage distribution to the geometry of the segment offset and the mutuality of segment propagation. By changing the applied stress and by controlling the segment tip growth, symmetric and asymmetric distributions of damage were produced. We describe which aspects of the generated damage zones satisfactorily correlate with field observations. Damage mechanics simulations are useful tools for studying the state of stress during dike emplacement.

1. Introduction

Dikes, particularly near their peripheries, are composed of arrays of en echelon segments. Likewise, en echelon arrays of cracks are abundant in a variety of geological environments and occur at length scales of millimeters to kilometers. For these cracks, dilation is driven by a combination of rock extension and fluid pressure acting on the crack walls [Pollard et al., 1975; Nicholson and Pollard, 1985]. The geometry of en echelon arrays and their associated rock deformation features are attractive subjects for structural analysis, perhaps enabling one to infer the state of stress acting when the arrays formed [Pollard et al., 1982; Rickard and Rixon, 1983; Nicholson and Pollard, 1985; Olson and Pollard, 1989; Cruikshank et al., 1991]. The present study focuses on the geometry of en echelon dike segments in porous sandstone, Makhtesh Ramon, Israel, and describes new patterns of rock deformation associated with their formation.

The segmentation mechanisms of dikes commonly depend on the surrounding host rock, the presence of preexisting fractures in the host rock, and the stress field acting along the dike propagation path. Previous studies attributed growth of segments to host rock inhomogeneity [Pollard et al., 1975], layering of the host rock [Baer, 1991], and depth-dependent rheological variations of the crust [Reches and Fink, 1988]. Currie and Ferguson [1970] explained segmentation as a result of dike intrusion into a preexisting segmented fracture system: magma fills a preexisting fracture, then a crack opens to a parallel preexisting fracture, and magma flows across this crack into the next fracture. Many arrays of dike segments are interpreted as breakdown of planar parent dikes [Anderson, 1951; Pollard et al., 1975; Delaney and Pollard, 1981; Delaney and Gartner, 1997]. In these cases the segments twist out of the parent dike plane under some shear stress resolved along that plane [Pollard et al., 1982]. The formation of segments may be the result of heterogeneities such as bedding interfaces and other structures that may perturb the stress field locally and impose mixed-mode I+III (opening and torsion) loading on closed or previously open cracks [Cruikshank et al., 1991; Cooke and Pollard, 1996]. Mixed-mode loading may alternatively be a result of spatial or temporal changes in the regional stress field [Pollard et al., 1982]. Detailed mapping of en echelon segment geometry and determination of the segment propagation directions provide useful information that helps to distinguish between the above segmentation mechanisms.

The stress field and the corresponding paths of en echelon dike segments have been intensively examined under linear-elastic-fracture-mechanics (LEFM) theory. Pollard et al. [1982] and Pollard and Aydin [1984] calculated how tip stresses change with gradual approach and overlap of adjacent en echelon segments. Later studies have explicitly accounted for the curvature of the segment tips in cross section [Olson and Pollard, 1989; Cruikshank et al., 1991; Olson and Pollard, 1991; Thomas and Pollard, 1993; Renshaw and Pollard, 1994]. Curving paths of en echelon cracks are attributed to the predominance of local crack-induced stresses over remote stresses during propagation. Nearly straight crack paths imply a small effect of local crack-induced stresses and the controlling influence of a remote crack-parallel compressive differential stress [Olson and Pollard, 1989]. Accordingly, the volume of rock mass around en echelon...
cracks could deform in different ways, depending on the propagation paths of the cracks [Pollard et al., 1975; Nicholson and Pollard, 1985]. For curving paths the deformation includes mainly rotation of rock between the segments; for straight paths it includes mainly bending and tensile fracturing of this rock [Nicholson and Pollard, 1985]. This study focuses on the geometric relations between the type of segmentation and the type of deformation, which further serves to constrain the state of stress during dike segmentation.

Our approach is to examine the stress field of interacting dike segments under a damage rheology model [Agnon and Lyakhovsky, 1995; Lyakhovsky et al., 1997a, b]. This model is different in two major aspects from the standard LEFM approach: (1) the host rock is treated as a nonlinear elastic material, with elastic moduli that explicitly depend on the damage distribution; and (2) the distributed damage evolves with deformation. Comparison between the stress field around an isolated pressurized crack in a damage-free linear-elastic material and in a damaged material shows significant differences in both orientations and magnitudes of the stress components near the crack tip [Weinberger et al., 1999]. Similar to the Barenblatt-Dugdale cohesive zone model [Barenblatt, 1962], the damage rheology model avoids infinite stresses at the segment tips and thus can consider the fracture processes and damage evolution around the interacting segment tips. The advantage of the damage model comparing to the Barenblatt-Dugdale model is that the former model considers the formation of distributed off-plane damage that is not localized along the dike plane. We examine the evolution of damage zones for different simulated initial geometries and stress fields. Then we compare the simulation results to our field observations and discuss the applicability of the simulated results for better estimating the state of stress acting during dike emplacement.

2. Geologic Setting

Makhtesh Ramon, southern Israel, is a deep erosional cirque along the axis of a N70°E trending asymmetric anticline (Figure 1). It exposes Triassic to Late Cretaceous sedimentary and Early Cretaceous igneous bodies, including basaltic and trachytic dikes that are part of a radial system. The northern, exposed part of this system comprises about 200 dikes [Zak, 1957], which extend up to 15 km from the estimated location of an unexposed central intrusion, south of Makhtesh Ramon. The studied dikes intrude the Jurassic Inmar Formation, which is built of massive, well-sorted, relatively undeformed porous sandstone [Richardson and Goldberg, 1988]. Most dikes are altered to kaolinite and intensely weathered, leaving erosion-resistant quartzitic walls along their contacts. They propagated in a predominantly subhorizontal direction, generating their own fractures [Baer and Reches, 1991]. Locally, these dikes are segmented, forming arrays of en echelon dike segments. Stratigraphic considerations indicate that the dike segments were arrested at depths between 1 and 0.5 km [Garfunkel and Derin, 1988; Baer, 1991].

In a previous study, Weinberger et al. [1995] mainly described dike-subparallel deformation bands beyond dike tips and adjacent to unsegmented dike walls in the Inmar Formation. These deformation bands are fine, roughly planar lamellae, lighter in color than the host sandstone, and appear as resistant ribs in the vicinity of the dikes. They are ~1 mm thick, consisting of crushed detrital quartz grains. In a few cases, these bands displace cross-bedded layers or other sets of deformation bands [Weinberger et al., 1995]. Such displacements are of the order of an individual band thickness. In that sense, the dike-related deformation bands are similar to deformation bands documented in sandstone by Aydin [1978], Aydin and Johnson [1983], and Antonellini et al. [1994] but are different from recently described compaction bands that have no shear offset along their planes [Mollema and Antonellini, 1996]. In this study we focus on the patterns of deformation bands around en echelon dike segments in the Inmar Formation, Makhtesh Ramon.

3. Dike Segmentation Geometry, Patterns of Rock deformation, and Segmentation Mechanisms

Deformation bands near en echelon dike segments typically form two types of patterns. We examine these patterns along two representative adjacent dikes (hereinafter dike 1 and dike 2) exposed in the same sandstone layers within a distance of <15 m, and composed of many segments. Figure 2 defines several geo-
3.1. Characteristics of Dike 1

3.3.1. Segmentation geometry. Dike 1 is ~210 m long and consists of 26 segments, 8 of which are shown in Figure 3. The segments are predominantly left-stepped (Table 1), forming a systematic array of en echelon nonoverlapping segments. They are typically several meters wide (see Figure 2 for dimensional terminology), 0.15 m thick, and offset by about 0.1 m. The twist angle of the array is ~3°. In plan view, each connector forms a curved line (Figure 3a), which is the trace of a curved surface dipping ~45-60° to the south (Figure 3b).

3.1.2. Propagation direction. The predominant propagation direction of dike 1 is ~60° upward to the north, parallel to the orientation of the steps [Baer, 1991]. More information is deduced from "fingers" (Figure 3b), which are elongated ridges and rills that are molded in the host quartzitic surfaces [Baer and Reches, 1987; Baer, 1991]. The tips of all fingers along dike 1 point northward, most fingers point upward subparallel to the long steps. However, close to the steps, always at their southern sides, the fingers change their orientations significantly and locally point horizontally, becoming perpendicular to the adjacent step.
Figure 3. (opposite) (a) Map of dike 1 en echelon array. Patterns of deformation bands associated with its steps are shown in insets 1-5. Enlarged area in inset 1 shows left-lateral displacement along crosscutting sets of deformation bands near the step. (b) Schematic geometric relationship between “fingers” and steps; the arrows indicate the local propagation direction (modified from Baer [1991]). (c) Definition of zones around connected segments.
Table 1. Data of Steps Along Dike 1 and Dike 2

<table>
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<tr>
<th></th>
<th>Number of Steps</th>
<th>Step-Related Deformation</th>
<th>Sense of Steps</th>
<th>Average Dike Thickness, m</th>
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<tr>
<td></td>
<td></td>
<td>Fan-like/Net-like, %</td>
<td>Left/Right, %</td>
<td></td>
</tr>
<tr>
<td>Dike 1</td>
<td>25</td>
<td>68/8*</td>
<td>84/16</td>
<td>0.15</td>
</tr>
<tr>
<td>Dike 2</td>
<td>15</td>
<td>7/93</td>
<td>100/0</td>
<td>0.10</td>
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<tr>
<th></th>
<th>Average Offset/Thickness (STD)</th>
<th>Average Overlap/Thickness (STD)</th>
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<tbody>
<tr>
<td></td>
<td>Steps Near Fan-like</td>
<td>Steps Near Net-like</td>
</tr>
<tr>
<td>Dike 1</td>
<td>0.8 (0.3)</td>
<td>8.7</td>
</tr>
<tr>
<td>Dike 2</td>
<td>1.4</td>
<td>7.8 (6.2)</td>
</tr>
</tbody>
</table>

*Step-related typical deformation is absent along 24% of the steps.

*STD, standard deviation.

(Figure 3b). The fingers document the initial flow of magma-generated fluids and might express the propagation direction of the magma-preceding fractures. Thus the initial predominant propagation direction of the dike segments is parallel to the steps (to the north, about 60° upward), but close to the steps the propagation direction of the dike segments is almost perpendicular to the steps [Baer, 1991, 1995]. Curved paths may also indicate the propagation direction of local fluid-preceding fractures [Kulander et al., 1979]. The morphology of segment walls along dike 1 suggests that propagation and linkage were achieved mainly by the southern segments curving toward the northern segments (i.e., one-segment propagation). Thus, locally, the southern segments propagated perpendicular to the steps, in agreement with the trend of fingers along the curved southern walls.

3.1.3. Pattern of deformation. The deformation associated with steps along dike 1 typically consists of fan-like patterns of subvertical deformation bands (Figure 4). The deformation bands are straight or slightly curved (in plan view), up to 4 m long, and are generally asymmetric about the dike plane. Typically, a straight deformation band merges with and continues beyond a segment wall and is oriented parallel to the general trend of the segment (Figure 3c, zones a and c). The slightly curved deformation bands are typically concave toward the dike wall. In a few cases, deformation bands displace each other by ~1 mm (Figure 3a, inset 1).

3.2. Characteristics of Dike 2

3.2.1. Segmentation geometry. Dike 2 is about 120 m long and consists of 15 segments, 12 of which are presented in Figure 5. The segments are generally connected and only rarely are they separated, forming a left-stepping en echelon array (Figure 5 and Table 1). The segments are several meters wide and 0.10 m thick, and their offsets are several times larger than the dike thickness (Table 1). Consequently, the twist angle is larger than that of dike 1 and exceeds 10°. In plan view, each connector forms a curved line (e.g., segments c, d, Figure 5).

3.2.2. Propagation direction. Information deduced from fingers is limited due to the two-dimensional nature of the exposures. The curved paths, however, suggest that segments commonly propagated perpendicular to the step and were linked mainly by one-segment curving toward an adjacent segment (one-segment propagation). In a few cases (e.g., Figure 5, inset 10), two adjacent segments simultaneously propagated toward each other along curved paths (i.e., two-segment propagation).

3.2.3. Pattern of deformation. The deformation associated with offsets along dike 2 typically consists of crosscutting sets of deformation bands that occur near the connectors between the overlapping segments (Figure 6). One set usually parallels the major segment of the dike, whereas the other subparallels the connector. In a few cases, it is possible to see that the connector-parallel set crosscuts the segment-parallel set (Figure 6b, inset). These patterns are generally confined to the overlapping region between the segments. Outside this region, dike-parallel deformation bands may be found up to a distance equivalent to...
four dike thicknesses away from the dike contact [Weinberger et al., 1995].

4. Field Observations: Discussion and Summary

4.1. Segmentation Mechanisms

The strong relationship between the segmentation geometry and the pattern of deformation bands (see below) provides an incentive to further interpret the segmentation mechanisms in dike 1 and dike 2 arrays. An adequate mechanism for dike segmentation should explain the geometric consistency within each array and the geometric differences between the two nearby arrays (Table 1). Since dike 1 and dike 2 intruded the same sandstone layers within a horizontal distance of <15 m, it is unlikely that host rock heterogeneities are responsible for the geometric consistency within each array or for the geometric differences between the

Figure 5. Map of dike 2 en echelon array. Insets 1-10 are enlargements of steps.
arrays. The absence of dike-parallel regional joints [Weinberger et al., 1995] indicates that these arrays did not form due to dike intrusion along preexisting arrays of en echelon joints. It is also unlikely that these arrays intruded into self-generated en echelon shear fractures, because the expected conjugate set of shear fractures [Reches and Fink, 1988] is generally absent. However, each array could be interpreted as breakdown segments of a planar parent dike that propagated at greater depth under mixed-mode conditions [Pollard et al., 1982]. The breakdown mechanism predicts that different states of stress are responsible for geometric differences between en echelon arrays, which, in turn, may explain the geometric differences between dike 1 and dike 2 arrays. Geometric differences may also be explained by differences between the stratigraphic levels in which segments of dike 1 and dike 2 were initiated. In that case, if the dike segments were increasingly twisted above the level of breakdown (Figure 2), then different levels of exposure may indeed correspond to spatial changes in the twist angles of these dikes.

Figure 6. (a) Photograph and (b) Map of deformation bands in the vicinity of overlapping connected segments (dike 2, Figure 5, inset 4). Two crosscutting sets of deformation bands follow the orientations of the segment boundaries, resulting in an intense deformation zone. The crosscutting relations are indicated.
4.2. Propagation Directions

Field observations of fingers and the morphology of segment walls along dike 1 indicate that all its segments preferably propagated northward. In addition, fan-like patterns of deformation bands around steps of dike 1 are generally asymmetric about the dike plane (Figure 4). Thus it is most likely that the asymmetric distribution of deformation is related, at least in part, to the preferred (asymmetric) segment propagation direction. Another possibility is that the segments were not perfectly oriented perpendicular to the least compressive principal stress direction in the rock. In that case, they propagated under minor shear stress that might enhance asymmetric distribution of deformation about the dike plane (the quantitative details of those effects are reported in section 6).

4.3. Patterns of Deformation

Deformation bands along segmented dikes show complex patterns near their irregularities. Nonoverlapping stepped segments are predominantly associated with fan-like patterns (Table 1 and Figure 7a). Overlapping connected segments are associated with
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Figure 8. (a) Schematic illustration of dike propagation paths under mixed-mode loading. The parent dike is subjected to tensile stresses (mode I loading) and horizontal right-lateral shear stresses (mode III loading). An en echelon array of segments forms under mode III loading at the top of the parent dike (breakdown level or level of incipient segmentation). 2w is the segment-width; 2l is the segment-length; 2s is the distance between centers of adjacent segments (spacing); 2o is the segment; 13 is the twist angle; P is the uniform internal pressure within the parent dike. (b) Rectangular cross section AA'BB' contains a two-segment array. Rotation of X1 and X3 axes by the twist angle 13 about X2 gives the orientations of x and y axes, respectively. The change of 11 with respect to Xi axis is provided by a rotation angle \( \psi \) about X2 (Figure 8b). 11 is positive), lying in the X2X3 plane (Figure 8a). Originally, the parent dike may have grown in a plane perpendicular to the maximum remote tension (tensile stress reckoned positive). Spatial or temporal changes of the orientation of 11 may induce a shear stress component parallel to the periphery of the parent dike [e.g., Pollard et al., 1982; Pollard and Aydin, 1988], and it may break into an echelon segments of width 2w (Figure 8a). The change of 11 with respect to the X1 axis is provided by a rotation angle \( \psi \) about X2 (positive anticlockwise, Figure 8b). For \( \psi \neq 0 \) the parent dike propagates under mixed-mode (I+III) loading, and segmentation is initiated. The twist angle 13 measures the discordance of the segments with respect to the trace of the parent dike in the X1X3 plane (positive anticlockwise), and 2s measures the spacing between adjacent centers of two segments (Figure 8).

The signs of \( \psi \) and 13 are the same, but their magnitudes are equal only for certain combinations of the applied stress and Poisson’s ratio \( v \) [Pollard et al., 1982]. The breakdown of a parent crack (or dike) depends on \( \psi \), the internal pressure \( P \), and the stress ratio \( R \) [Pollard et al., 1982; Delaney et al., 1986]:

\[
R = \frac{(2P + \sigma_1^* + \sigma_3^*)}{(\sigma_1^* - \sigma_3^*)}.
\]

The inequality \( P > -\sigma_1^* \) is required for the parent crack to be open. Applying the criterion in which cracks grow from a parent-crack tip perpendicular to the local least compressive stress
The form of $R$ as a function of $\beta$, $\psi$, and $v$ is [Abelson and Agnon, 1997]

$$R = \frac{\sin 2\psi}{\sqrt{2-v}} \tan 2\beta - \cos 2\psi.$$

Thus a twist angle $\beta$ measured in the field corresponds to a range of values $(\psi, R)$ assuming a constant Poisson’s ratio ($v=0.25$). High values of $R$ are related to high internal pressure $P$, high remote mean normal tensional stress, and low differential stress $(\sigma_1^r-\sigma_3^r)$.

At the level of breakdown the new segments are oriented perpendicular to the local least compressive stress [Pollard et al., 1982, $\sigma$, in Figure 4] independent of whether $\beta$ equals or not $\psi$. At later stages of growth, the segments propagate away from the parent crack, exiting its K-dominant zone but possibly retain their initial orientation with respect to the parent crack ($\beta$ is constant) [e.g., Cooke and Pollard, 1996, Figure 1]. The assumption of constant $\beta$ during growth is a consequence of the plane strain conditions applied in many works on segment interaction (e.g., Pollard et al., 1982; Olson and Pollard, 1989), and this assumption is also applied here. The segments grow along planes that carry the maximum tensile stress and zero shear just in front of remote stresses. The output of the model is the damage intensity $\sigma$ and the stress field everywhere around the segments. The non-dimensional variable $\alpha$ may be envisioned as an effective local density of cracks and other flaws in a material that undergoes deformation. Similar properties of the material are represented by contours of equal $\alpha$ intensities, termed “isodamage” lines. The evolving damage modifies the effective elastic properties of the material around the notches, leading to local “destruction” of one or several numerical elements of the host rock. Destruction of an element is related to the vanishing of Young’s modulus upon failure for one-dimensional stress-strain relation or to the loss of convexity of the elastic energy for three-dimensional stress-strain relation [Lyakhovsky et al., 1997b, equations 14, 15]. In that sense, the destruction is similar to stress drop upon failure in rock mechanics experiments, which occurs when $\alpha$ reaches its critical value [Lyakhovsky et al., 1997b, Figure 1]. The destroyed elements are then filled with magma and a propagation of the segment ends occurs. We simulate damage-controlled quasi-static dike propagation [Meryiaux et al., 1999] assuming constant internal fluid pressure within the entire segment. Lyakhovsky [1999] shows that this model correctly reproduces experimentally observed relations for the velocity of the quasi-static mode 1 propagating cracks. A complete analysis of dike propagation velocity requires simultaneous solution of the coupled equations governing host rock deformation and fluid flow [Lister and Kerr, 1991; Rubin, 1993] and has not been attempted in the present study. The present model allows us to simulate the trajectory of the propagating en echelon dike segments, coalescing of adjacent cracks, and evolution of distributed damage around them.

6. Simulation of Deformation Near Interacting en Echelon Dike Segments

6.1. Damage Rheology Model

In order to understand the segment interaction, connection, and the associated deformation we applied a damage rheology model [Lyakhovsky et al., 1993, 1997a]. This model allows the examination of off-plane damage evolution around the segments. The model enables us to simulate the segment propagation and damage evolution. In this section we identify factors that control the states of deformation and stress associated with segment interaction and connection. The damage model describes the cumulative effect of flaws and fractures in the damaged region and does not aim to account for each dike-related fracture separately.

Agnon and Lyakhovsky [1995] adopted damage rheology for simulating damage evolution during the growth of dikes. Comparison between the present approach to damage analysis and other approaches was extensively discussed by Lyakhovsky et al. [1993] and Lyakhovsky et al. [1997a, b]. Fast Lagrangian analysis of continua (FLAC) algorithm [Cundall, 1989; Poliakov et al., 1993] with modifications accounting for a nonlinear elasticity and damage evolution is used in the present calculations. The Lagrangian approach assumes that the change of grid coordinates is according to displacements and thus provides the capability for applying large strains. In particular, the shape of a simulated pressurized segment is continuously changing and not related to the grid size but is a result of the interaction between the internal fluid pressure and host rock deformation. The exact segment opening displacement is out of the resolution of the figures presenting results of the simulations. However, it can be recognized after zooming in, as presented by Weinberger [1998, Figure 4.12].

The stress and damage fields are computed in two dimensional area assuming plane strain conditions. To propagate two segments, initial notches or highly damaged regions subjected to a uniform internal pressure are placed en echelon. The input of the model consists of the elastic moduli of the host rock, the damage rate coefficient, and boundary conditions that correspond to the remote stresses. The output of the model is the damage intensity $\alpha$ and the stress field everywhere around the segments. The non-dimensional variable $\alpha$ may be envisioned as an effective local density of cracks and other flaws in a material that undergoes deformation. Similar properties of the material are represented by contours of equal $\alpha$ intensities, termed “isodamage” lines. The evolving damage modifies the effective elastic properties of the material around the notches, leading to local “destruction” of one or several numerical elements of the host rock. Destruction of an element is related to the vanishing of Young’s modulus upon failure for one-dimensional stress-strain relation or to the loss of convexity of the elastic energy for three-dimensional stress-strain relation [Lyakhovsky et al., 1997b, equations 14, 15]. In that sense, the destruction is similar to stress drop upon failure in rock mechanics experiments, which occurs when $\alpha$ reaches its critical value [Lyakhovsky et al., 1997b, Figure 1]. The destroyed elements are then filled with magma and a propagation of the segment ends occurs. We simulate damage-controlled quasi-static dike propagation [Meryiaux et al., 1999] assuming constant internal fluid pressure within the entire segment. Lyakhovsky [1999] shows that this model correctly reproduces experimentally observed relations for the velocity of the quasi-static mode 1 propagating cracks. A complete analysis of dike propagation velocity requires simultaneous solution of the coupled equations governing host rock deformation and fluid flow [Lister and Kerr, 1991; Rubin, 1993] and has not been attempted in the present study. The present model allows us to simulate the trajectory of the propagating en echelon dike segments, coalescing of adjacent cracks, and evolution of distributed damage around them.

6.2. Boundary Conditions and Model Setup

Propagation of a given en echelon dike segment array, in which $\beta$ and $s$ are prescribed, is simulated under different applied stresses. In the first set of simulations the segments propagate along a principal axis ($\psi=\beta$), and the applied stress is controlled by changing the magnitudes of the remote differential stress. In the second set of simulations with ($\psi=\beta$) the applied stress was varied by changing $\psi$ in steps of 15° and calculating $R$ according to equation (2) for a given $\beta$. We assume that the studied level is
close to the paleosurface (see geologic setting) and the effective lithostatic pressure (i.e., the weight of the rocks above the studied level minus the pore pressure at this level) is negligible. The case that the studied level is ~1000 m below the paleosurface was analyzed by Weinberger [1998] and is presented briefly in section (6.3.4.).

For the sake of convenience, we introduce a local coordinate system with the x axis oriented perpendicular to the segment width and the orthogonal y axis parallel to the segment width (Figure 8b). The local (x,y) coordinate system is rotated by an angle $\beta$ with respect to the parent dike orientation presented by $X_1$ and $X_2$ axes in Figure 8. For simplicity, we consider only restricted range of boundary conditions, assuming that $\sigma_1=\sigma_3$ and $\sigma_1=P/R$ (equation (1), internal pressure $P$ is given). Then the principal stresses $\sigma_1'$ and $\sigma_3'$ are rotated by an angle ($\psi-\beta$) around a vertical axis and the three components ($\sigma_{xx}'$, $\sigma_{yy}'$, $\sigma_{xy}'$) of the remote stress are calculated. These components should be applied infinitely far from the simulated segments. To accomplish this, we apply a special numerical procedure to approximate the constant remote stress conditions. First, we calculate the initial elastic strain of the damage-free material that corresponds to the remote stresses. Then, we apply mirror conditions for the top/bottom, and zero displacements along the left/right sides of the simulated area and insert the initial pressurized segments (notches). The total strain in the simulated area is a sum of the initial elastic strain and the calculated strain around the pressurized segments. The left/right sides of the simulated area are placed far enough from the segments that their displacements are negligibly small and the applied fix condition reproduces well the constant remote stress conditions. To illustrate possible changes in the geometry of the array due to one-segment propagation, the internal pressures of segment A and segment B (Figure 8b) were kept at $P$ and $P/2$, respectively.

In the first simulation the initial segment (notch) widths were a tenth of the final width (Figure 9a), thus increasing the necessary computations up to segment connection. To reduce the computation time several initial configurations were tested in which the initial segment widths were greater than $w/5$. The tests indicate that starting the simulation with initial segment widths of $4w/5$ provides a reliable solution in the interacting area between the segments [Weinberger, 1998] and also significantly reduces the necessary computation time. Hence further simulations of interacting segments were initiated with segment widths of $4w/5$. The numerical results do not depend on the choice of the grid size. This is illustrated by Weinberger [1998] and by Weinberger et al. [1999, Figure 2].
6.3. Simulation Results

6.3.1. Segment propagation under variable remote differential stresses ($\beta=5^\circ$).

The first simulation considers propagation of two segments toward each other, with $\beta=5^\circ$ and initial segment width $w/5$, where $w$ is the segments' final width (Figure 9a). The segments are subjected to a uniform internal pressure ($P=5$ MPa) and zero remote differential stress. At the initial stage, before the onset of segment propagation, a pair of localized damage lobes spread out symmetrically around the segment planes (Figure 9b). At this stage the interaction between segments is negligible, and thus the shape and intensity of the damage zones are similar to damage distribution near an isolated pressurized segment [Agnon and Lyakhovsky, 1995].

Similar to mode I cracks, the segments start to propagate in their own plane (Figure 9c), and, simultaneously, the distributed damage develops into "lobes" of intense damage with their long axis obliquely oriented to the plane of the segments. Since the host rock was initially damage free, there is a transient stage from the onset of damage to self-similar quasi-static behavior. The expected increase of the stress ratio $(\sigma_1-\sigma_3)/P$ (maximum differential stress normalized by the internal pressure computed around the segment ends during stages of mutual propagation) with the width of the segment about constant, being compensated by the spreading out of damage lobes (Figure 10). Continued propagation of the segments enlarges these lobes and the intensity of the damage increases in a self-similar manner (compare Figures 9c and 9d).

The stress ratio $(\sigma_1-\sigma_3)/P$ increases until the width to spacing ratio ($w/s$) approaches 0.8 (Figure 10). At this stage the segments start to interact mechanically, imposing shear stresses upon each other and enhancing damage accumulation mostly in the region between them. The propagation direction is no longer in-plane, and the stress ratio increases dramatically until the segments overlap at $w/s=1.1$. Subsequently, a connected configuration is achieved, beyond which point the differential stress drops to zero and subsequently the maximum and minimum principal stress become interchanged (Figure 10). The stress drop at the time of segment connection implies that final failure of the host material surrounding the segments occurs at this point. Subsequently, intruding magma connected between the segments and contributed to the final stabilization of the segmented configuration (Figure 9e).

The next series of simulations examines the effect of the applied stresses on the damage distribution around two propagating segments subjected to a uniform internal pressure of $P=5$ MPa. The remote differential stress ($\sigma_{xx}-\sigma_{yy}$) was varied from $-0.4P$ (segment-parallel tension) to $1.2P$ (segment-perpendicular tension) in steps of $0.2P$. Well-defined oblique damage lobes were produced under low magnitudes of remote differential stress. The obliquity of the distributed damage is described by the angle $\varphi$ (Figure 11, inset), which varies with respect to the stress ratio $(\sigma_1-\sigma_3)/P$. Thus, the shape of the damage zone is sensitive to the applied stress (Figure 11) and can be described by simple geometrical means. However, in other cases shown in sections 6.3.2. and 6.3.3., the geometrical complexity of the damage zones could not be described by a single angle $\varphi$.

6.3.2. Two-segment and one-segment propagation under different pairs of $(\psi, R)$, and $\beta=5^\circ$.

The orientation of the applied stresses were changed between $75^\circ \leq \psi \leq 15^\circ$ in steps of $15^\circ$ and $\beta=5^\circ$ (simulations 1-5, Table 2). For different pairs of $(\psi, R)$ (namely, different states of stress) the simulations produced different damage distributions (Figure 12a).
Figure 11. Variations in the obliquity of the distributed damage (denoted by an angle $\phi$) versus the stress ratio $(\sigma_1 - \sigma_3)/P$. $\phi$ measures the angle between two tangents to an isodamage line. The tangents begin at a point of intersection between the isodamage line and a line that is parallel to the top/bottom side and cuts through the middle of the connector (see inset); $\phi$ is slightly sensitive ($\pm 5^\circ$) to chosen isodamage line and is positive when measured clockwise.

For a two-segment propagation the damage distribution with respect to a middle point along the connectors is antisymmetric, whereas the obliquity of the damage lobes increases with increasing $\psi$ (Figure 12a). For a one-segment propagation (simulations 6-10, Table 2) the asymmetry of damage distribution significantly increases with $\psi$ (Figure 12b). For small values of $\psi$ ($\psi<30^\circ$) (and, consequently, small values of $R$, $R<20$) the damage distribution is only slightly asymmetric with respect to the segment planes with no obliquity. For moderate values of $\psi$ ($45^\circ \leq \psi \leq 60^\circ$) (and, consequently, large values of $R$, $R>20$), the asymmetry and obliquity of the distributed damage increase (Figure 12b). These sets of simulations indicate that in certain regions around segment A only minor damage is distributed (compare Figures 12a and 12b), whereas in other regions damaged lobes are pronounced. Large values of $\psi$ ($90^\circ > \psi > 60^\circ$) (and small values of $R$, $R<20$) further increase the asymmetry.

6.3.3. Two-segment propagation under different pairs of $(\psi, \beta)$, and $\beta=10^\circ$.

The next pair of simulations (simulations 11-12, Table 2) tested the effects of increasing the twist angle $\beta$ from $5^\circ$ to $10^\circ$ on the damage distribution of two propagating segments. Geometrically, increasing $\beta$ implies larger bridges; mechanically, it implies smaller values of $R$ (equation (2)). The appropriate values of $R$ for $\psi=30^\circ$ and $\psi=45^\circ$ (simulations 11-12, Table 2) produce dif-

### Table 2. Values of Variables Used for Simulations With Different Pairs of $(\psi, R)$

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Internal Pressure, MPa</th>
<th>Seg A</th>
<th>Seg B</th>
<th>State of Stress $\beta$, deg</th>
<th>$R$</th>
<th>Elastic moduli, GPa $\lambda_0$</th>
<th>$\mu_0$</th>
<th>Kink Angle $\theta_0$, deg</th>
<th>Distributed Damage, Qualitative Remarks</th>
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<td>5</td>
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Figure 12. Isodamage lines of $\alpha=0.02$ during segment connection for variable pairs of $(\psi, R)$ and $\beta=5^\circ$; $\psi$ increases in steps of 15$^\circ$. (a) Two-segment propagation (simulations 1-5, Table 2). (b) One-segment propagation (simulations 6-10, Table 2). Insets: orientations of the remote principal stresses with respect to the echelon segments in the $X_1X_3$ plane. See Table 2 for the values of $(\psi, R)$.

6.3.4. Two-segment propagation under an effective lithostatic pressure, and $\beta=5^\circ$.

En-echelon segments may be continuous or discontinuous in plan view depending on the state of stress prevailing during their propagation. This is illustrated for two segments propagating under a uniform internal pressure of 10 MPa and an effective lithostatic pressure of 5 MPa (Figure 14; simulations 13-14, Table 2). In these simulations the effective lithostatic pressure significantly reduces the distribution and intensity of damage compared to simulations with a similar driving pressure but zero effective lithostatic pressure. This is because effective pressure inhibits material failure. Nevertheless, the bridge zone between the en echelon segments fails and the segments connect, forming a continuous stable configuration (simulation 13, Table 2). Simulation 14 (Table 2) in which the magnitude of the right-lateral shear stress is higher than that predicted by the pair $(\psi, R)$ produced out-of-plane distribution of damage and propagation, resulting in a discontinuity in plan view (Figure 14b). Thus discontinuous segments are more likely to result from high magnitudes of shear stress while forming, but the relative importance of other factors such as the offset to spacing ratio and confining pressure has not been addressed yet.

7. Mechanical Analysis: Discussion and Summary

The simulations illustrate the sensitivity of the damage distribution to the geometry and relative position of the segments and to the mutuality of segment propagation. Damage is mostly enclosed within contours of high maximum shear stresses but also within contours of high tensile stresses ahead of the segment tips. Variations in the obliquity of the damage distribution (in cases where the principal stresses are parallel and perpendicular to the segment planes) are described by the angle $\phi$, which varies with respect to the stress ratio $(\sigma_1-\sigma_3)/\sigma$ (see Figure 11). Simulations of one-segment propagation under a series of remote differential stresses and of pairs of $(\psi, R)$ indicate that the intensity of damage is significantly reduced around the stagnant segment tip. These simulations produce an asymmetric distribution of damage about the segment planes, which is significantly different from the symmetric distribution of damage due to two-segment propagation. Relatively large bridges suffer high shear stresses, localized deformation, and intense damage during the segment propagation. These variations in the distribution and intensity of the damage provide the framework for constraining the possible orientation and relative magnitudes of the stress field that prevailed during dike emplacement. We first discuss the possible correlation between field observations and the simulation results, and then we infer the associated state of stress during segment interaction.

7.1. Correlation Between Observed and Simulated Damage Zones

For the purpose of correlation between field observations and damage simulations, deformation band density maps of deformation zones around en echelon dike segments were prepared in the following way. A counting square of size 10x10 cm$^2$ was moved over selected field maps of rock deformation associated with dike segments (Figure 3). Adjacent squares overlapped each other by an area of 5x10 cm$^2$. The deformation-band density $D_f$ was estimated from the relation

$$D_f = \frac{\sum_{i=1}^{n} L_i^2}{A},$$

where $L_i$ is the length of a particular deformation band and $n$ is the number of deformation bands counted within a square area of size $A$. The data obtained were smoothed by averaging every point with its nearest (eight) neighbors, and then presented graphically (Figure 15). At present, the scaling between the deformation band density $D_f$ and the damage intensity $\alpha$ is not
Figure 13. (a) and (b) Two segment propagation for $\beta=10^\circ$ and contours of isodamage lines for $0.02<\alpha<0.1$ (contour interval 0.005). Segments may intrude into regions of high damage intensity and thus are expected to produce horns. Increasing $\psi$ in Figure 13b increases the tendency for horn evolution and overlapping (simulations 11 and Figure 13a and 13b, respectively, Table 2). (c) Trajectories of maximum principal tensile stress in the bridge zone just prior to overlapping of segments (simulation 11). (d) Trajectories of maximum principal tensile stress in the bridge zone after overlapping of segments (simulation 11). Trajectories are presented within an area of significant magnitude of stress, $p/10$, where $p$ is the internal pressure. Arrows mark a location of significant stress variations. Enlargement of this location indicates that right-lateral shear is resolved on a fracture parallel to the connector during connection of the segments.

clearly understood. However, the two variables should be correlated because both represent fracture processes in the host rock during dike emplacement, suggesting that some generalizations can be cautiously made.

We chose two cases to show the applicability of the model. The first case is for nonoverlapping stepped segments (dike 1). The deformation bands around nonoverlapping steps of dike 1 are asymmetrically distributed around the dike plane, forming damage within zones a, b, and c, but are almost absent within zone d (Figure 3). The sense of shear in specific locations within these zones could be deduced (Figure 3; insets 1 and 2), and the fingers along dike 1 indicate that all its segments propagated northward (one-segment propagation). The twist angle of the en echelon array is relatively small ($\beta=5^\circ$). Thus one-segment propagation and $\beta=5^\circ$ are incorporated in the model setup for this array. Other simplifying approximations used include growth under conditions of negligible effective lithostatic pressure and a relatively low angle of internal friction and stiffness value for the host rock (sandstone). Simulations are adjusted to fulfill two requirements: (1) produce the observed (field) asymmetric distribution of damage, including intense damage within zone b, moderate damage within zones a and c, and minor damage within zone d, and (2) produce the observed sense of shear in specific locations around the segments.

Simulations 6-10 (Table 2) were carried out under negligible effective lithostatic pressure using one-segment propagation and small twist angles. A qualitative comparison between a deformation band density map (Figure 3, inset 5) and a damage distribution map produced by simulation 8 shows that $D_1$ and $\alpha$ are asymmetrically distributed (Figure 15). They are predominantly developed in zone b and are less developed in zones a and c. $D_1$ almost vanish in zone d, in contrast to $\alpha$, which is somewhat enhanced in zone d. Nevertheless, excluding these discrepancies, the damage zones obtained in simulation 8 satisfactorily correlate with the field observations.

By examining the modeled orientations of $\sigma_1$ during the failure of the bridge one can predict if shear is resolved on a certain fracture plane within the damaged lobe and in what sense. This is useful for comparison between the simulation predictions and the shear observed on certain fractures in the field. Simulation 8 indicates that planes of high shear stress are obliquely oriented with respect to segment B (within zone b) and that left-lateral shear must be resolved on such planes during the connection of the segments (Figure 15b). This is in agreement with the observed crosscutting relations of deformation bands in zone b (Figure 3, inset 1).

The results of simulation 8 are further examined herein in an attempt to predict the orientations of potential deformation bands. The present field observations indicate that deformation bands are associated with shear and are similar to that described by Aydin [1978]. Thus it is likely that they initially formed along planes of high shear stress [Friedman and Logan, 1973] and that their orientations are approximately parallel to trajectories of maximum shear stress. Other mechanisms of deformation band formation would require other correlation. For example, pure compaction deformation bands would orient perpendicular to
The orientations of potential deformation bands in zones a and c are less clear (Figure 15b). In particular, the shear trajectories provide no explanation for formation of dike-parallel deformation bands (of primary shear origin) in front of the segment tips during segment connection (Figure 15a). However, trajectories of minimum principal tensile stress (at 45° from trajectories of maximum shear stress) suggest that dike-parallel deformation bands beyond segment tips (zones a and c) may be enhanced by the tensile stress at the segment tip during early stages of segment propagation and subsequently sheared during later stages of segment interaction. In that sense, deformation bands around dike segments formed in a complex way and may have a different origin than dike-parallel deformation bands near an isolated dike tip [Weinberger, 1998].

The second case is that of overlapping connected segments (dike 2). Deformation bands around connectors of dike 2 generate intense damage mainly in the bridges (Figure 6b). In some cases, the sense of shear in specific locations within these zones could be deduced (Figure 6, inset). In addition, field observations suggest that one- and two-segment propagation directions are associated with the segments of dike 2, and the twist angle of the array is larger (β=10°) than that of dike 1 (Table 1). Two-segment propagation and β=10° are incorporated in the model setup for this array. Other simplifying approximations used include growth under conditions of negligible effective lithostatic pressure and a relatively low stiffness value for the host rock (sandstone). Simulations are adjusted to fulfill three requirements: (1) generate intense damage mainly in the bridge; (2) produce the observed sense of shear in specific locations around the segments; and (3) increase the tendency for overlapping and horn growth.

Simulations 11-12 (Table 2) integrated a large twist angle (β=10°) with a two-segment propagation under negligible effective lithostatic pressure. Both simulations produced intense damage within the bridge, and relatively low intensity of damage outside this zone (Figures 13c and 13d). The simulations indicated that right-lateral shear is resolved on fractures parallel to the connector during connection of the segments, in agreement with the observed crosscutting relations (Figure 6b). Moreover, trajectories of the maximum principal tensile stress σ1 indicate that the local stress field gradually changes during segment propagation within the bridge zone (Figures 13e and 13d). These changes are significantly more pronounced within the bridge zone than outside, enhancing the formation of the net-like pattern of deformation bands in the bridge. The absence of fan-like patterns around dike 2 is due to the formation of large bridges and the relatively low intensity of damage outside the bridge region.

Comparison between the two dikes reveals that R values for dike 1 model are higher than those for dike 2 model (Table 2) and are consistent with the larger twist angle of dike 2 than that of dike 1. Consequently, the offsets and bridges along dike 2 are larger, the bridges suffer relatively high shear stresses and intense damage during the segment propagation, and the tendency for overlapping increased (Figure 7). Thus the R values appear capable of well characterizing the stress state responsible for both the different geometries of the interacting segments and for the different damage distribution around them.

7.2. Inferring the Stress State From Damage Zones Around Dike Segments

Key aspects of the model-derived damage zones are consistent with field observations and thus may constrain the stress state during dike emplacement. In practice, the method outlined in section 7.1, whereby a simulation is adjusted to fit the observations, may be used to relate the geometry of the distributed damage around the dike segments to the stress state prevailing during their formation. In models of dike 1 the stress state that best agrees with the observations is 60°≥ϕ≥30° and moderate to high stress ratio R (R=20). In models of dike 2 the stress state that best agrees with the observations is 45°≥ϕ≥30° and moderate to low magnitudes of stress ratio R (R=10). Thus the results suggest that dike 1 and dike 2 grew under somewhat different stress states. Variations in the stress field might have occurred during the dike intrusion period in the Ramon, which lasted 10 Myr or less [Baer and Reches, 1991]. Changes both in the far field (i.e., regional stress field and the stress field associated with a central intrusion) or in the local fields (i.e., heterogeneities such as adjacent structures and bedding interfaces) may contribute to variations suggested by our simulations.

The present model calculates the stress state under plane strain conditions and assumes that the segments are located out of the influence of the parent dike. This implies that the associated deformation should be distributed far from the breakdown level and that t>>w, where l is the segment half-length and w is the segment half width (Figure 8). This assumption could not be verified in the field because the breakdown level is unexposed. The maximum exposed dike length (measured along the overall propagation direction of a segment) is ~5 m, similar to the maxi-
Figure 15. Comparison between field observations and simulated damage zones around two en echelon dike segments (see text). (a) Fan-like pattern of deformation bands (Figure 3, inset 5). (b) Trajectories of maximum shear stress are enclosed within an isodamage line of $\alpha=0.02$. Potential deformation bands along planes of maximum shear stress are indicated. (c) Deformation bands density map. (d) Simulated damage zone (simulation 8, Table 2).

mum deformation zone width measured adjacent to dike walls [Weinberger et al., 1995]. Thus, at the level of observations, the segments and the associated deformation are most likely located outside the (parent) dike process zone. The absence of the (parent) dike-subparallel deformation bands near the segments of dike 1 (Figure 3) provides additional support for the above assumption. If the above assumption is incorrect and $l\approx l$, then the present two-dimensional model neglects the effects of the spatially varying stress field of the parent dike process zone and that of the interaction between the parent dike and the en echelon segments. Although considerable insight has been gained, models for the complete interaction and for three-dimensional twisted segment surface are required to examine the details of breakdown, propagation, and arrest. Three-dimensional effects such as those enhanced by a vertical front of one segment exceeding the vertical front of an adjacent segment have not yet been examined.

Low-pressure zones at the segment ends may play role in producing inelastic deformation off the dike plane. Once the two segments overlap, they impede one another, and propagation is limited by their stress interaction, rather than by viscous flow. In that case, the assumption of uniform internal pressure is quite reasonable. Shortly before the segments overlap, propagation might be rate-limited by viscous flow. However, if the segments are thick enough near their adjacent ends due to stress interaction [Pollard et al., 1982, Figure 15], then the length scale of significant pressure drop near the segment ends is probably short. On the other hand, very low effective lithostatic pressure relative to the excess internal fluid pressure may enhance dynamic propagation of the segment ends and leave the magma behind. This possibility has not been addressed in this study.

8. Conclusions

1. Patterns of deformation bands along segmented dikes in porous sandstone are strongly related to the geometry of en echelon dike
segments. If the offset to thickness ratios and overlap to thickness ratios are smaller than one, segments are typically associated with a fan-like pattern of deformation bands; if the offset to thickness ratios and overlap to thickness ratios are larger than one, segments are typically associated with a net-like pattern of deformation bands.

2. The stress field governing the breakdown mechanisms explains the differences in geometry and in rock deformation between the studied en echelon segment arrays.

3. The asymmetry of rock deformation about the dike plane (in the form of fan-like patterns of deformation bands) suggests that nonmutual segment propagation and minor shear plays an important role during dike segmentation.

4. Localization of deformation within bridges (in the form of net-like patterns of deformation bands) indicates that these regions suffer from high shear stresses.

5. Damage distribution around offset dike segments reflects the stress state and segment geometry and is related to $\beta$, $\psi$, and $R$ variables.

6. The damage model produces different types of segment connections, depending on the arrangement of the segments, the mutuality of segment propagation, and the stress state.

7. The damage zones and predicted orientations of deformation bands yielded by the model satisfactorily correlate with field observations, and may be used to constrain the stress state during dike emplacement.

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References


