Flow patterns of magma in dikes, Makhtesh Ramon, Israel

Gidon Baer
Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel

Ze'ev Reches
Department of Geology, Hebrew University, Jerusalem, Israel

ABSTRACT

Directions of magma flow were measured in a system of radial dikes in Makhtesh Ramon, Israel. The flow directions were determined from field observations of segments, fingers, grooves, and groove molds of the dikes. The study indicates that the mean axis of magma flow is subhorizontal toward the north, in agreement with the direction of divergence of the radial dike system. Two modes of flow were observed: (1) regular, bedding-parallel flow in the well-stratified rock units and (2) irregular, meandering flow in the massive rock units. It is suggested that corrugated dike walls in well-stratified host rocks cause magma channelization, and random or self-generated restrictions in massive host rocks cause the apparent meanders. Furthermore, the major lithologic boundaries in the host units strongly affect segmentation of the dikes.

INTRODUCTION

Dikes propagate by flow of magma into dilating tensile fractures. Propagation directions of dikes may be inferred from the geometry of the dike system and from flow indicators preserved in the dikes and in the host rocks. For example, radial dike systems indicate outward propagation of the magma from a central source (Ode, 1957), and dike segments and fingers can indicate growth mechanism and local propagation directions (Pollard et al., 1975). The formation of segments and fingers was attributed to host-rock inhomogeneity, which enables magma at the periphery of an intrusion to accelerate ahead of the bulk of the intrusion (Pollard et al., 1975).

Flow in dikes can be vertical, delivering magma upward; lateral, delivering magma in a horizontal direction (Harker, 1909); or mixed (Gudmundsson, 1984). Seismological investigations support lateral magma flow in parts of some dikes of Iceland and Hawaii (Einarsson and Brandsdottir, 1980; Duffield et al., 1982). Abrupt changes of dike propagation directions over short distances, from near vertical to almost horizontal, were found in the San Rafael Desert, Utah; they indicate the complexity of dike injection processes (Gartner and Delaney, 1985). Some small-scale flow indicators, such as fingers and grooves, are preserved only along the dike

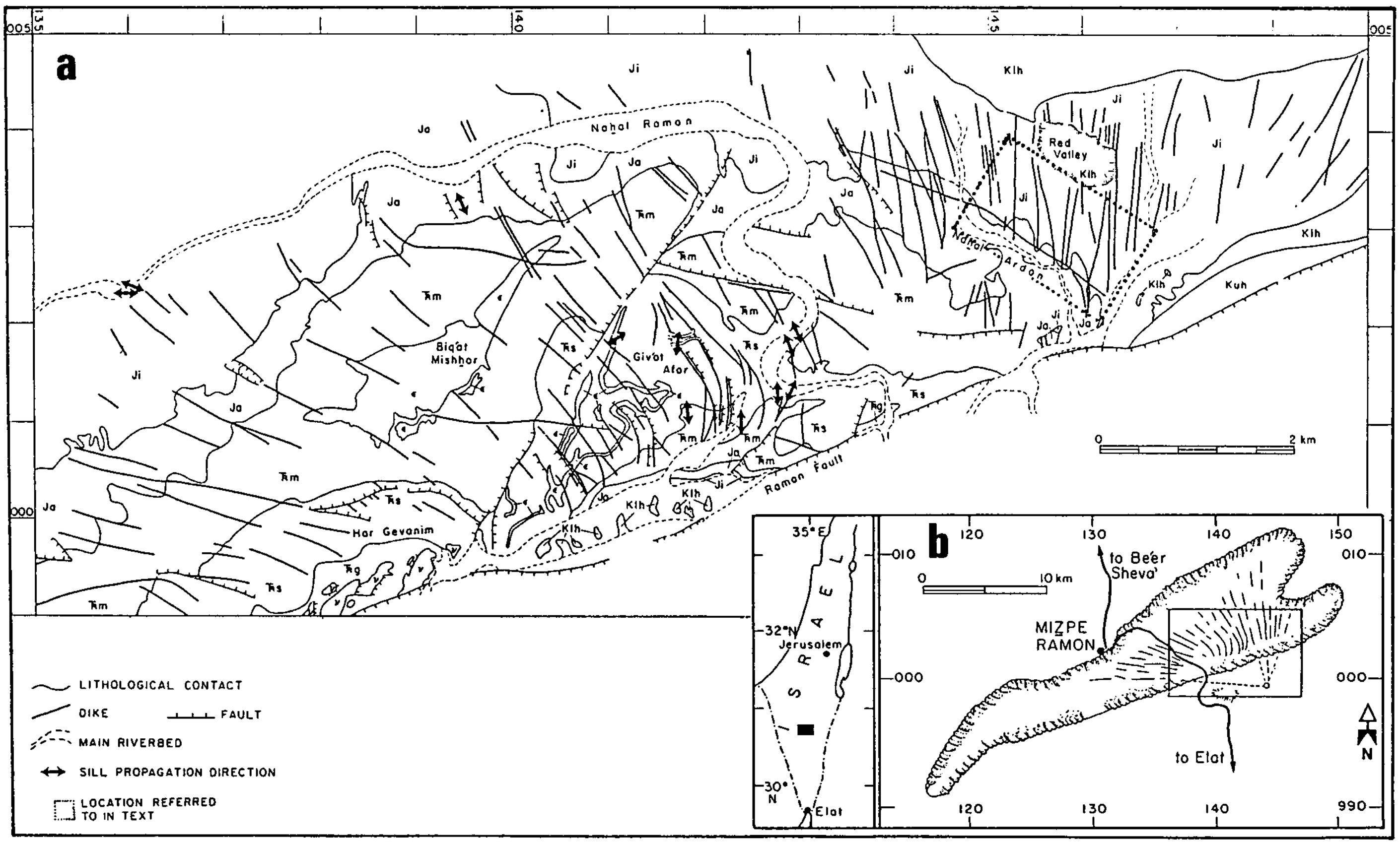

Figure 1. a: Simplified geologic map of radial dike systems in eastern Ramon (geology after Zak, 1968). Trg = Gevanim Fm., Triassic; Trs = Saharonim Fm., Triassic; Trm = Mohila Fm., Triassic; Ja = Ardon Fm., Jurassic; Ji = Inmar Fm., Jurassic; Klh = Hatira Fm., Lower Cretaceous; Kuh = Hazera Fm., Upper Cretaceous. Double-head arrows indicate measured propagation directions in sills (after Baer, 1987). b: Schematic map showing major trends of dikes in Makhtesh Ramon and inferred center of radial system (after Zak, 1957).

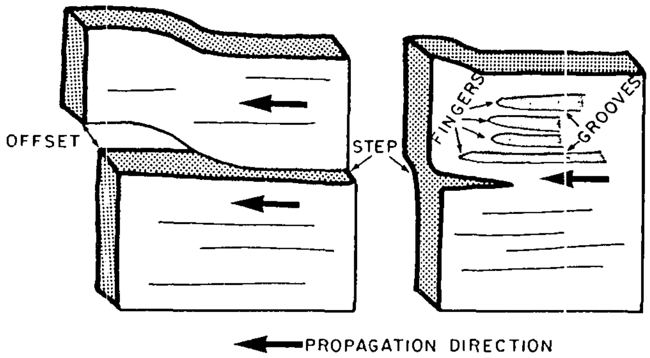

Figure 2. Idealized relation between dike flow indicators and propagation direction.

Figure 3. Offset segment in basaltic dike that intrudes Ardon Formation, Nahal Ardon. Edges of segments coincide with contact between two members of Ardon Formation.

walls. Because the dike walls are the first to solidify, these indicators record the direction of initial magma flow. We assume that the direction of initial flow represents the direction of dike propagation. We document here the flow pattern within dikes in a radial dike system by describing the flow indicators and their field distributions. We also discuss possible mechanisms for the observed patterns.

GEOLOGIC SETTING

Numerous basaltic and trachytic dikes of Late Jurassic to Early Cretaceous age are exposed in eastern Makhtesh Ramon, Israel. These dikes form a radial system (Fig. 1) having a divergence center south of the Ramon fault (Zak, 1957, 1968). Both basaltic and trachytic dikes seem to occupy the radial system and to trend in similar directions. Many of the dikes are altered into kaolinite, making it difficult to recognize the original composition of the rock.

This study is based primarily on dikes that intrude the Lower to Middle Jurassic units (Fig. 1). These units include the well-stratified Ardon Formation, composed of limestone, dolomite, and shale, and the Inmar Formation, composed of massive sandstone and shale lenses. Many dikes also occur in Lower to Middle Triassic limestone and marl of the Saharonim Formation. Dikes occur less frequently in the Upper Triassic gypsiferous layers of the Mohila Formation and Lower Triassic sandstone and shale of the Gevanim Formation. Sills are also common and are described in Baer (1987).

CRITERIA FOR FLOW DIRECTIONS

The directions of magma flow in the Ramon dikes were determined from the following indicators (Fig. 2): (1) segments—subunits of a dike that range in width from a few tens of centimetres to a few hundreds of metres; one may observe stepping segments, in which the intrusion is segmented but remains continuous, and offset segments (Fig. 3), in which the intrusion appears locally noncontinuous; (2) fingers—elongated, wavy irregularities of dike rock along its contact with host rock; and (3) grooves—the depressions that form between the fingers.

Pollard et al. (1975, Figs. 13–16) showed that the long axes of the planes separating segments, fingers, and grooves are parallel to the magma flow direction. These directional indicators, however, do not always show the sense of propagation; for example, a horizontal step in a north-trending dike indicates horizontal flow either northward or southward. The sense can be determined by the direction in which fingers terminate.

Most of the dikes in the Inmar Formation are altered and weathered, and the preserved flow indicators are groove molds (Fig. 4), which are

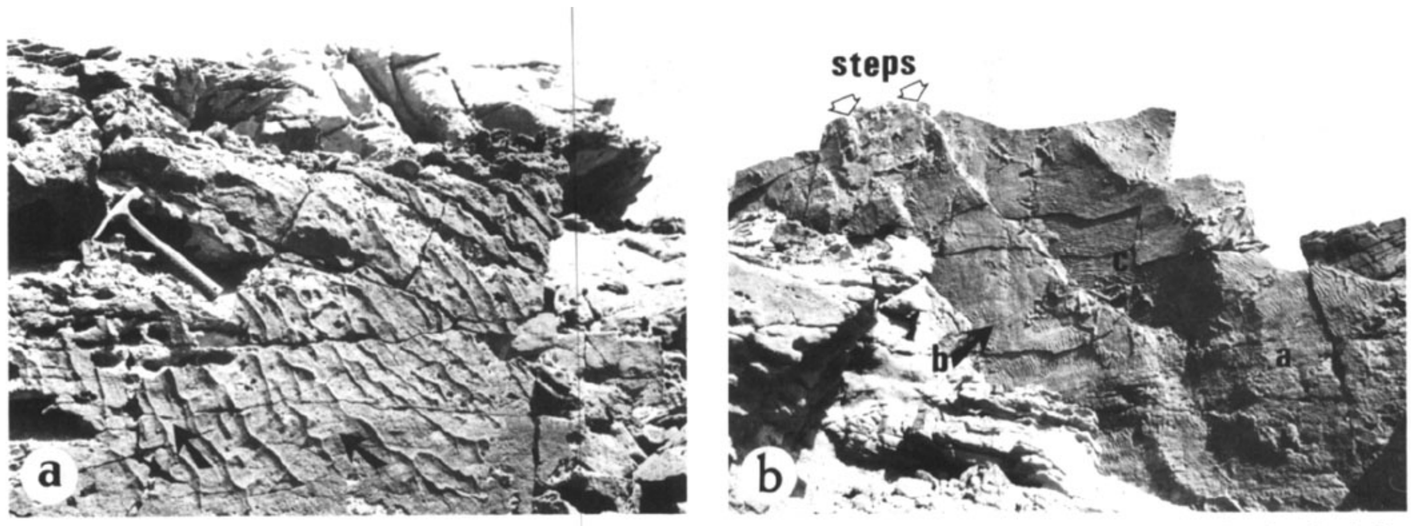

Figure 4. Groove molds and finger terminations on quartzitic host walls along dike contacts in Inmar Formation, south of Red Valley (location in Fig. 1a). a: Dendritic pattern; arrows mark flow direction. b: Groove molds in quartzitic host rocks at proximity of an edge of segment. Flow lines are generally parallel to step, areas a and b, but locally may be 45° to step direction, area c.

the molds of grooves and imprints of the associated fingers in the erosion-resistant host quartzitic walls. The groove molds are discontinuous and display dendritic patterns that show consistent convergence in one direction representing finger terminations on the dike wall. The groove molds, therefore, indicate the direction and sense of the flow (arrow in Fig. 4a).

OBSERVED FLOW DIRECTIONS IN RAMON DIKES

Figure 5 displays the orientations of flow indicators measured on dikes that intrude to the Jurassic units. These indicators are relatively rare along dikes in the Triassic units. To simplify the presentation, each dike was rotated about a vertical axis into a north-south trend; maximum rotation is 20°.

In the Ardon Formation the flow indicators are subparallel to the bedding planes; i.e., they plunge slightly to the north and deviate by as much as a few degrees from the intersection of the bedding with the dike wall. The edges of the large segments in these dikes are associated with lithologic contacts. For example, seven exposed dikes, distributed over a 2-km-wide region, are *all* segmented and offset along the contact between the lower and upper members of the Ardon Formation (Figs. 3, 5a). This contact separates well-bedded limestone and dolomite from a massive unit of brown shale above.

Flow indicators in the dikes in the Inmar Formation show semicontinuous changes from vertically upward flow to almost vertically downward flow, flow directions changing abruptly over distances of less than 50 m (Fig. 5a). The most irregular patterns seem to be spatially associated with the termination zones of large segments (Fig. 4b). In these zones the inclinations of the molds may locally deviate from the inclination of the offset of the host segment by 45° or even more. These local irregularities probably reflect irregular flow patterns within the molten magma at a segment margin. Even though the directions of flow vary intensely, all flow axes have a south to north component, and the mean direction of magma flow is 4° downward to the north (Fig. 5b).

DISCUSSION

Two flow patterns are apparent in Figure 5: bedding-parallel flow in the Ardon Formation (southern parts of the dikes) and meandering flow in the Inmar Formation (northern parts). These patterns of magma flow are most likely related to the nature of stratification of the host sedimentary units.

We suggest that the intrusion of a dike into the well-stratified Ardon Formation is most likely analogous to the fracturing of laminated metals in laboratory extensional tests. Such tests usually include fracturing of bonded plates of metal alloys that have different mechanical properties (Embury et al., 1967; Cox and Tetelman, 1973; Alic and Danesh, 1978). Two configurations of crack propagation were investigated (Fig. 6a): crack arrester, where the crack propagates perpendicular to the laminae, and crack divider, where the crack propagates parallel to the laminae. The crack divider geometry is similar to the geometry of dikes propagating in a subhorizontal direction into subhorizontal layered rock units. Under crack divider tests, the

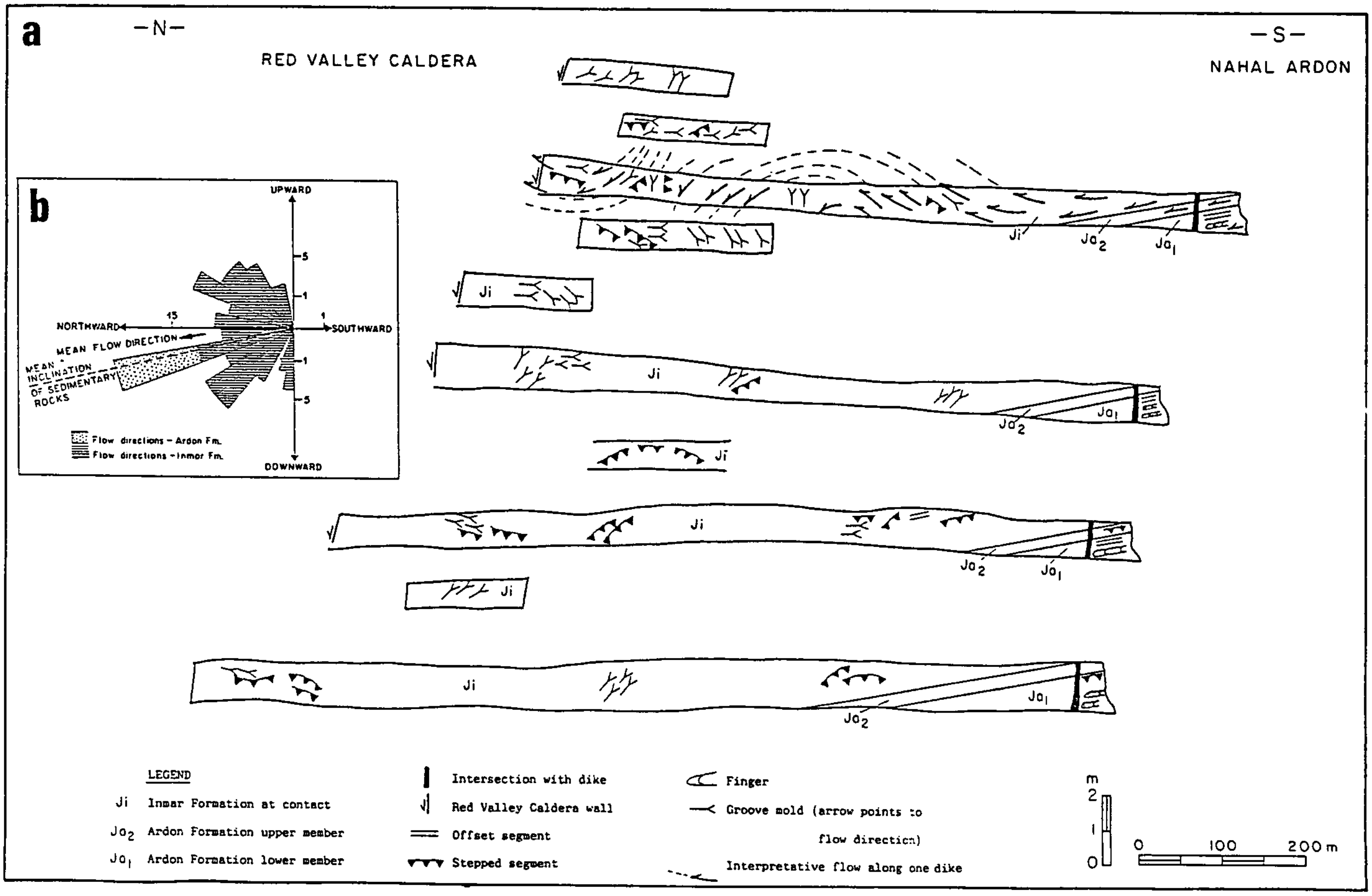

Figure 5. a: Distribution of flow indicators on exposed walls of 10 dikes (location shown in Fig. 1a). Interpretative continuous flow trajectories are shown for third dike from top. b: Rose diagram of all measured flow directions on above and in adjacent dikes. Number of measured points = 116.

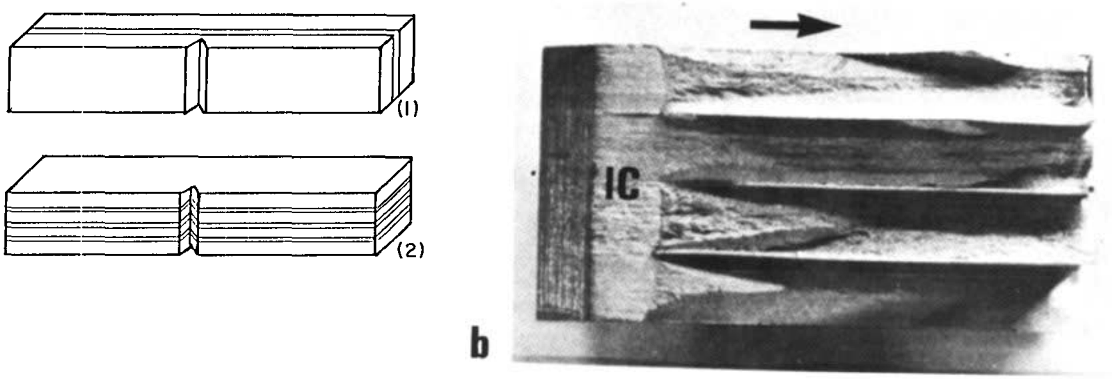

Figure 6. Tensile fracturing of laminates. a: Relation of fractures to laminae in crack arrester (1) and crack divider (2) geometries (after Embury et al., 1967). b: Fracture surface in crack divider configuration in aluminum alloy laminate (from Cox and Tetelman, 1973). Arrow shows crack propagation direction from initial crack (IC).

main crack splits into a series of smaller cracks that propagate individually and channel through the laminate subunits. The crack surface is stepped, long furrows and ridges being parallel to the laminae (Fig. 6b).

The magma flowing in the dikes in the Ardon Formation most likely encountered similar corrugated fracture surfaces. The furrows and ridges form a series of alternating wide and narrow conduit zones, parallel to bedding. Because of the lower resistance to flow in the wider conduits (Delaney and Pollard, 1982), the magma is channeled into these wide zones and flows more easily parallel to bedding. Segments may also form parallel to bedding surfaces, as demonstrated by the offset of several dikes along the same lithologic boundary (Figs. 3, 5). Such boundaries cause large enough inhomogeneities in the host rocks to enhance segmentation (see also Pollard et al., 1975).

In contrast to the bedding-parallel flow in the Ardon Formation, the groove molds on the dike walls in the Inmar Formation show no consistent relation to the observed bedding surfaces (Figs. 4, 5). The massive sandstone of the Inmar Formation lacks strong lithologic variations and may be regarded as a homogeneous rock unit. We think that the meandering pattern represents the characteristic magma flow in dikes that intrude a homogeneous medium. We suggest that the lack of preexisting channeling features permits the magma to flow spontaneously, subject to magma-driven constraints; the nature of these constraints is unknown.

Gudmundsson (1984) suggested mixed vertical and lateral flow of magma in dikes of Iceland. Our observations demonstrate that such mixed flow occurs and can be documented. However, the schemes of flow in the sedimentary host rocks of Ramon—i.e., bedding-parallel and meandering—most likely differ in detail from the flow in the basaltic host rocks of Iceland. Further, offsets of dikes along lithologic boundaries were also observed in Iceland (Gudmundsson, 1983), although these offsets were not attributed to the lithologic stratification.

SUMMARY

Dike-wall geometry and dike imprints on adjacent host rock enable us to determine the trend of flow trajectories and the sense of flow. The magma in the radial dike system of Ramon flowed northward in a mean subhorizontal direction from a magma source located south of the present Ramon fault. Differences in the magma flow patterns appear between dikes in well-stratified, layered units and in poorly stratified, massive units. These differences may reflect channeling flow in the stratified units and nonchanneling, meandering flow in the poorly stratified units.

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ACKNOWLEDGMENTS

This study was mainly supported by project No. 20024 of the Geological Survey of Israel, and partly supported by fund DE-FG02-85ER13320, U.S. Department of Energy. We thank Paul Delaney for introducing us to flow patterns in dikes and for his helpful suggestions; Marie Jackson and Jon Fink for stimulating discussions during field trips in Utah and Colorado; Ed Beutner, Wendell A. Duffield, Jon Fink, and Agust Gudmundsson for critically reviewing the manuscript and for their constructive remarks; and Sa'adya Levy, David Vadai, Rivka Backman, and Yosef Levy for their technical assistance. The study is part of Baer's Ph.D. studies at the Hebrew University, Jerusalem.

Manuscript received December 1, 1986
Revised manuscript received March 2, 1987
Manuscript accepted March 6, 1987

Reviewer's comment

Provides important ideas and evidence for determining the propagation direction and fluid flow within dikes and other hydraulic fractures.

Edward Beutner

Printed in U.S.A.