Earthquake-induced clastic dikes detected by anisotropy of magnetic susceptibility

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ABSTRACT

Clastic dikes form either by passive deposition of clastic material into preexisting fissures or by fracturing and injection of clastic material during seismic shaking or passive overpressure. Because of their similar final geometry, the origin of clastic dikes is commonly ambiguous. We studied the mechanisms of clastic dike formation within the seismically active Dead Sea basin, where hundreds of clastic dikes crosscut soft rock of the late Pleistocene lacustrine Lisan Formation. We analyzed the anisotropy of magnetic susceptibility (AMS) of clastic dikes of known origin and defined characteristic AMS signatures of depositional or injection filling. We discovered that passively filled dikes, which contain brownish silt resembling local surface sediments, are characterized by an oblate AMS ellipsoid and vertical minimum susceptibility axis V_3. Dikes that contain green clayey sediment connected to a mineralogically identical detrital layer of the Lisan Formation are characterized by a triaxial AMS ellipsoid, well grouped subhorizontal and parallel to the dike walls' maximum susceptibility axis V_1, and subvertical intermediate susceptibility axis V_2. Field evidence and AMS analysis indicate that most of these dikes were emplaced by injection inferred to be due to seismically triggered fluidization. This novel application of the AMS provides a petrofabric tool for distinguishing passively filled dikes from injection dikes and, where appropriate, for identifying the latter as seismites.

Keywords: clastic dikes, anisotropy of magnetic susceptibility, Dead Sea transform, seismites.

INTRODUCTION

Clastic dikes are discordant, tabular bodies composed of weakly to strongly lithified clastic detritus. The mechanism of clastic dike formation is poorly understood, and interpretation of field observations is commonly ambiguous (e.g., Aspler and Donaldson, 1985). Two end-member mechanisms have been proposed: depositional or Neptunian clastic dikes formed by passive deposition of clastic material into preexisting fissures that are open to the Earth's surface (e.g., Eyal, 1988); and injection clastic dikes formed dynamically by host-rock fracturing and injection of unlithified clastic sediment slurries from below. Injection dikes are commonly formed during seismic shaking and are among the most impressive liquefaction features occurring during strong ($M \geq 6.5$) earthquakes (McCalpin, 1996). Jolly and Lonergan (2002) suggested that injection clastic dikes may also form by overpressure-induced hydraulic fracturing at depths greater than several hundred meters.

In this study we use anisotropy of magnetic susceptibility (AMS) to explore the emplacement mechanism of dozens of Holocene clastic dikes that crosscut late Pleistocene soft rocks in the Ami'az Plain, Israel, within the seismically active Dead Sea basin. We determined unique AMS fabrics in dikes whose field relations unequivocally establish them as either depositional filling or injection structures. The AMS fabrics and field observations of the latter structures reflect injection of clastics at high flow velocity simultaneously with dynamic fracturing of the soft host rock, most likely during earthquake events. The strong correlation between the AMS fabric and dike-filling mechanism indicates that AMS analysis is an effective tool for resolving the emplacement mechanisms of clastic dikes, and that it may also be helpful in recovering paleoseismic records in complex geological settings.

GEOLOGIC SETTING

The Ami'az Plain is a downfaulted block located adjacent to the Sedom salt diapir (Zak, 1967), on the western margin of the Dead Sea basin, along the segmented Dead Sea transform (Fig. 1; Garfunkel, 1981). The rocks exposed in the Ami'az Plain belong to the late Pleistocene Lisan Formation, which consists mostly of lacustrine laminae of aragonite and fine detritus, dated between ca. 70 and 14 ka by U series and ^{14}C (Haase-Schramm et al., 2004, and references therein). A thin veneer (<2 m) of eolian and fluvial sediments covers large parts of the plain. Paleoseismic records based on breccia layers reveal numerous $M > 5.5$–6 earthquake events during the past 70 k.y. (e.g., Marco and Agnon, 1995; Enzel et al., 2000), as well as several $M > 7$ earthquake events (Begin et al., 2005).

We mapped ~250 clastic dikes in the Ami'az Plain, previously noted by Zak (1967) and Marco et al. (2002), by means of aerial photographs and field surveys (Data Reposi-

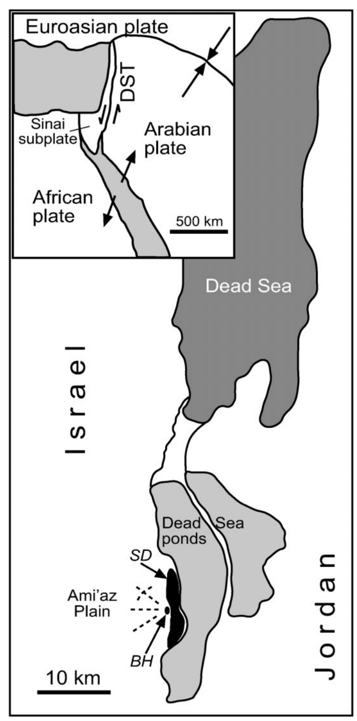

Figure 1. Location maps showing regional setting of Dead Sea basin (inset) and Ami'az Plain study area. Clastic dikes are marked schematically with broken lines. DST—Dead Sea transform; SD—Sedom diapir; BH—Black Hill.

Figure 2. Clastic dike 18 m high, filled with green clayey sediment cross-cutting Lisan Formation and branching toward surface. Dike architecture resembles that of bifurcated dynamic fracture during upward propagation (e.g., Bahat, 1991) and shows geometry similar to that of injection dike presented by McCalpin (1996, p. 366). Lisan laminae are not displaced across dike, indicating that clastic dike is extensional fracture.

tory Fig. DR1[1]). The dikes exposed in the canyon walls of Wadi Perazim within the Lisan Formation are extensional fractures (Figs. 2 and 3), indicating brittle Holocene fracturing. The dikes are as long as 1 km, 30 m high, and 0.4 m wide, and are arranged mainly in radial and tangential geometry. The radial traces, which span a sector of 70°, converge toward the Black Hill dome. This led Marco et al. (2002) to suggest that the dike pattern is related to the local stress exerted by doming.

[1]GSA Data Repository item 2006019, Figure DR1, detailed location map of clastic dikes, Figures DR2–DR4, rock magnetic data, and Figure DR5, streaked AMS fabric of an injection dike, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

Figure 3. Wide (~0.4 m) clastic dike open at surface filled with brownish silt. Source of fill is veneer of eolian and fluvial sediments, which cover Ami'az Plain.

We distinguish between two types of dikes. Most abundant are dikes composed of green clay, silty quartz, and aragonite, with a composition similar to that of the lower layers of the Lisan Formation. In many dikes, a continuous connection between the dike fill and a green clayey layer of the Lisan Formation is observed, clearly indicating that these structures are injection dikes. Several of these dikes branch toward the surface (Fig. 2). Occasionally, these dikes thin upward; some fail to reach the surface. Less common are depositional dikes composed of brownish silt (which occur sporadically with horizontal bedding planes), which resembles the veneer of surface sediments (Fig. 3). These dikes always intersect the present topographic surface and commonly have a large opening in their upper part.

AMS APPLICATION FOR CLASTIC DIKES

Hypothesis

Foliation and lineation of a magnetic fabric may form as a result of transport, deposition, and deformation of rocks (Borradaile and Henry, 1997). These features are commonly associated with AMS, which has been used to resolve current directions in sediments (Tarling and Hrouda, 1993; Liu et al., 2001) and flow directions in magmas (Baer, 1995; Abelson et al., 2001; Aïfa and Lefort, 2001). AMS has also been correlated with strain in rocks and tectonic deformation of sediments (Parés et al., 1999), and has been used to characterize soft-sediment deformation (Schwehr and Tauxe, 2003).

We use AMS to distinguish between depositional and injection clastic dikes. We adopt Tauxe's (1998) terminology, where the eigenvalues τ_1, τ_2, and τ_3 correspond to maximum, intermediate, and minimum values of the magnetic susceptibility, and the principal eigenvectors are V_1, V_2, and V_3, respectively. In sedimentary rocks, we expect a well-grouped vertical V_3 direction and dispersed V_1 and V_2 directions within a horizontal plane (hereafter termed sedimentary fabric). The values of the associated τ_1 and τ_2 are indistinguishable and characterized by an oblate AMS ellipsoid. In moderate currents, grain imbrication results in slightly off-vertical V_3 directions, and V_1 directions (in lower-hemisphere projection) are antiparallel to the flow direction (Tauxe, 1998; Liu et al., 2001). In high-energy currents with particles entrained, V_1 directions are perpendicular to the flow direction, and V_3 directions are commonly streaked, resulting in prolate or triaxial AMS ellipsoids (Tauxe, 1998, and references therein).

On the basis of the above-mentioned previous works, we hypothesize that depositional dikes will display a sedimentary AMS fabric, and that injection dikes will display prolate or triaxial AMS ellipsoids. In the latter case, two types of AMS ellipsoids may occur, depending on the flow velocity of the injected clastics. Under moderate flow velocities, V_1 is expected to be parallel to the flow vector, whereas under high flow velocity, V_1 is expected to be perpendicular to the flow direction and streaked V_3 distribution may evolve. In the latter case, the flow direction will be indicated by either the V_2 or V_3 direction (Tauxe, 1998; Moreira et al., 1999). In both cases, the eigenvectors should be well grouped, characterizing a flow fabric.

Sampling Strategy and Methods

We recovered 312 samples from 14 clastic dikes and country rocks. We carved 2.5 cm cylinder pedestals with a sharp knife and placed on them on plastic araldite glue–coated cylinders with no AMS signal. The dikes were sampled across their width and along their height, 8–35 specimens in each. On the basis of field observations, two of the dikes are depositional and four are injection dikes; the other eight seem to be injection dikes, but their connection to the source layer is unexposed. For comparison between the AMS fabric of the injection dikes and the source layer, we sampled 10 specimens from the lower part of the Lisan Formation. To test whether the AMS fabrics are primary, and to detect possible imbrication and shearing, we sampled the dike margins more intensively than the dike centers.

The AMS was measured with a KLY-3S Kappabridge at the Geosciences Laboratory, University of Rennes 1, France. The ellipsoid shape parameters were derived according to Tauxe's (1998) procedure. To detect a possible postemplacement deformation, we also measured the natural remanent magnetization of several pilot specimens with a cryogenic magnetometer. To characterize the magnetic carriers of the dike's infill and the Lisan source sediment, we used 20 thermomagnetic curves and 20 hysteresis loops of specimens from the margins and the centers of the dikes.

RESULTS

The results of the AMS fabric of three representative clastic dikes and of the Lisan source layer are presented in Figure 4 and Figure DR5 (see footnote 1). The fabric of the Lisan source layer is typically sedimentary (Figs. 4A, 4E) and exhibits an oblate AMS ellipsoid, indicated by the overlap of the 95% confidence level of τ_1 and τ_2 (Fig. 4I). The depositional dikes, represented here by dike T, also exhibit a sedimentary magnetic fabric similar to that of the Lisan source layer (Figs. 4B, 4F, 4J). The injection dikes, represented here by dike Q and dike Tk, have different and distinctive AMS fabrics. In these dikes, the V_1 directions are well grouped, subhorizontal, and parallel to the dike strike, the V_2 directions are well grouped and subvertical (Figs. 4C, 4G, 4D, 4H), and the distributions of the V_3 directions are commonly streaked (Figs. 4D, 4H; Fig. DR5 [see footnote 1]). Moreover, in the extensively sampled dike Tk, the V_1 directions everywhere along the dike margins and at the center are parallel to the dike strike, whereas the trends of the V_2 directions are slightly imbricated. The bootstrap statistics eigenvalues define distinct triaxial AMS ellipsoids (Figs. 4K, 4L). Noticeably, triaxial AMS ellipsoids are detected in samples closely located (<0.2 m) as well as in that vertically located away (<20 m) from the source Lisan layer.

In addition, the natural remanent magnetization directions of the clastic materials show. Holocene–Recent field, regarded as evidence for stable orientation of the magnetic particles after emplacement (Fig. DR2). Thermomagnetic curves show that the dominant magnetic carrier of the green clayey sediment of the dike and the source layer is titanomagnetite (Fig. DR3), which characterizes the Lisan Formation (Marco et al., 1998). Hysteresis loops show that the green material is mostly a pseudo-single to multidomain grain series (Fig. DR4), which is preferable for AMS studies (Borradaile and Henry, 1997). The ratio Mr/Ms (remanent to saturation magnetization) for the green material is near 0.1, which is typical of the detrital Lisan laminae (Marco et al., 1998). X-ray diffraction analyses show that both the source layer and the injected dikes contain aragonite, a typical constituent of the Lisan sediments. In contrast, aragonite is not found in the brownish fill of the depositional dikes. The similar composition of the injection dikes and the Lisan sediments strengthens our field observations about the connection between these bodies.

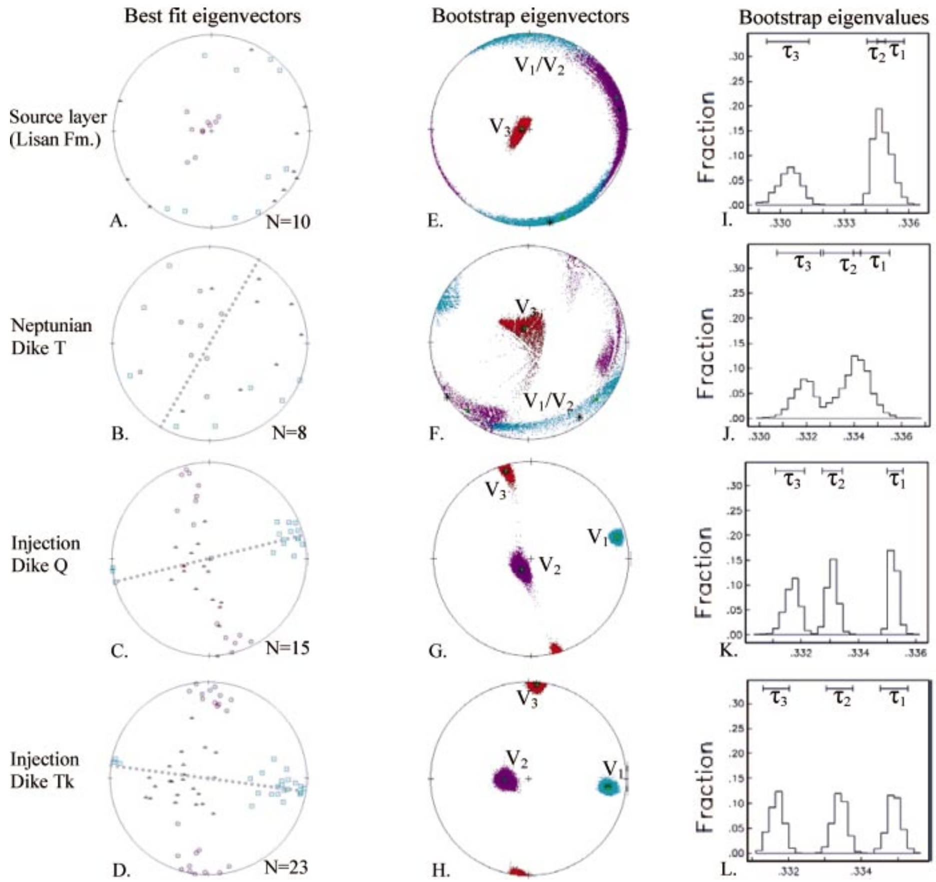

Figure 4. Anisotropy of magnetic susceptibility (AMS) for Lisan source layer and three clastic dikes (dikes T, Q, and Tk). A–D: Lower-hemisphere, equal-area projections of AMS eigenvector orientations. Squares—V_1, triangles—V_2, and circles—V_3. E–H: Lower-hemisphere, equal-area projections of bootstrapped AMS eigenvector distributions. I–L: Histograms of bootstrapped eigenvalues: τ_1, τ_2, and τ_3 with 95% confidence bounds. Dashed lines mark dike strikes. Dikes Q and Tk were sampled above their source layer, implying that in this sector, flow should have vertical component. Because at these localities V_2 is subvertical and slightly imbricated, it is likely that V_2 directions are local flow indicators. Mean magnetic susceptibility of depositional dikes is ~250 × 10^{-6} SI and that of injection dikes and their source layer is ~70 × 10^{-6} SI. Different susceptibility is interpreted as indicating different sedimentary origins (e.g., Liu et al., 2001). Fm—Formation.

DISCUSSION AND CONCLUSIONS

Our results show that depositional dikes in the Ami'az Plain are characterized by sedimentary oblate AMS ellipsoids, whereas the injection dikes are characterized by distinct triaxial AMS ellipsoids. We interpret the latter AMS fabric as evidence that the sediments within the injection dikes were emplaced by flow. We maintain that consequent deformation due to dike-perpendicular compaction and expulsion of pore water contained in the injected clastics may have slightly modified the recently acquired flow fabric, but could not modify its original triaxial shape (Parés et al., 1999). These results support our hypothesis that AMS fabrics can be used to determine the emplacement mechanism of clastic dikes whose origin cannot be definitively established by field observations.

The natural in situ water (brine) content of the green clayey Lisan source sediment is between 27% and 36%, which is within or close to the range obtained from the liquid limit of this sediment (Arkin and Michaeli, 1986). Shaking and squeezing the Lisan sediment causes a fast expulsion of pore water, a drastic loss of shear strength, and consequent material flow (Arkin and Michaeli, 1986). We refer to this flow of clayey particles from the source into the evolved dikes as fluidization (e.g., Mohindra and Bagati, 1996).

Our AMS results strongly support simultaneous injection of clastic materials with fracturing, or at least the opening of existing clamped fractures in the Lisan host rock. Some of the injection dikes are continuous fractures that extend up to the Earth's surface. Most probably the simultaneous fracturing and injection of sediments prevented deposition of clastic materials from above, and the collapse of the weak and friable fissure walls. If the fissures were open for some time, then sedimentary fabric should have developed within the dikes; but such a fabric was not found, even in dikes that were intensively sampled (e.g., dike Tk). The consistent subhorizontal V_1 directions trending parallel to the dike walls across the width of the dikes imply that the dike fill was emplaced during or immediately after fracture propagation. Moreover, the upward bifurcation of the dikes (Fig. 2) is consistent with a dynamic and upward emplacement of the injection dikes.

Two main mechanisms can explain the formation of the injection dikes in the Ami'az Plain: shallow fluidization, commonly triggered by seismic shaking during earthquakes (e.g., McCalpin, 1996); and deep (several hundreds of meters) fluidization resulting from excess pore pressure due to compaction (Jolly and Lonergan, 2002, and references therein). The stratigraphic position of the Lisan Formation at the top of the local stratigraphic sequence, where no overlying strata were ever deposited, suggests that the fluidization is shallow and not related to compaction. Had fluidization and fracturing resulted from compaction, then similar dikes could be expected to have developed regionally and would not be restricted to the Ami'az Plain.

The proximity of the dikes to an active plate boundary favors earthquakes as the major trigger for fluidization. Paleoseismic studies indicate that several strong earthquakes ($M \geq 6.2$) occurred during the past 15 k.y. along the Dead Sea fault zone (Begin et al., 2005, and references therein).

Our AMS analysis, field observations, and interpretations demonstrate that the formation of most clastic dikes in the Ami'az Plain is associated with fluidization triggered by strong earthquakes along the Dead Sea transform after deposition of the Lisan Formation (i.e., after 15 ka). Although the directions of these dikes may be dictated by stresses exerted by the local doming at the eastern margin of the Ami'az Plain (Marco et al., 2002), our study demonstrates a viable earthquake-induced mechanism for their formation. The new application of AMS provides a petrofabric tool to identify clastic dikes as seismites, which, with good age constraints, may provide an important addition to paleoseismic records.

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