PERGAMON

Journal of Structural Geology 21 (1999) 703–710

JOURNAL OF STRUCTURAL GEOLOGY

Sigmoidal wall-rock fragments: application to the origin, geometry and kinematics of en échelon vein arrays

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Received 19 January 1998; accepted 17 March 1999

Abstract

Wall-rock fragments found within en échelon vein arrays may provide valuable information on the origin of vein systems, shear zone kinematics, and vein geometry. These fragments are sigmoidal and comprise intact rock between adjacent veins or fragments enclosed within individual veins. We present field examples of sigmoidal rock fragments within en échelon veins that grew as opening-mode fractures in response to an applied simple shear. By virtue of their unique shape and alignment of pre-existing fabric, we demonstrate how small wall-rock fragments may be used as kinematic indicators as well as to predict geometries of individual veins and entire vein arrays. Such a tool may be especially useful in mining exploration where the precise boundaries of large veins are unknown, or in stockworks where the rock is composed primarily of vein material.

1. Introduction

'En échelon' refers to a geometric alignment of fractures within a defined zone in which individual fractures step systematically and overlap each other by varying amounts. The definition of 'en échelon' as it relates to fracture arrays should be purely based on descriptive geometry rather than origin, because markedly different mechanisms and boundary conditions may lead to strikingly similar structures. For example, en échelon vein arrays may develop (1) within simple shear zones (Hancock, 1972; Durney and Ramsay, 1973; Beach, 1975; Ramsay and Huber, 1983, 1987), (2) as sets of cross joints that terminate against pre-existing systematic joints (Dyer, 1988), (3) as overlapping joint segments belonging to the same set (Olson and Pollard, 1991), and (4) as fringe cracks that develop due to breakdown of a single parent crack (e.g. Pollard et al., 1982; Kulander and Dean, 1985; Nicholson and Pollard, 1985; Bahat, 1986; Younes and Engelder, 1999). In cases where a simple shear origin for en échelon veins has been established, the veins may serve as effective kinematic indicators (e.g. Ramsay and Huber, 1983, 1987).

In this note we report a new structure observed in en échelon vein arrays referred to as 'sigmoidal wall-rock fragments'. These fragments of host rock resemble the sigmoidal geometry of the veins in which they are enclosed, and thus may provide valuable information on the origin, orientation, and kinematics of the overall vein system. Our goals are to (1) provide a detailed description of the sigmoidal wall-rock fragments, (2) discuss the origin of these structures based on well-constrained field relations, and (3) demonstrate the potential of sigmoidal rock fragments to serve as kinematic indicators, indicators of principal stress orientations, and to predict overall vein array geometry.

2. Geologic setting and outcrop description

En échelon gypsum veins are prominently exposed in an outcrop of the Turonian (~90 Ma) Ora

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0191-8141/99/$ - see front matter
PII: S0191-8141(99)00074-7

Formation located near Ma'aleh Gerofit along the western margin of the Dead Sea rift in southern Israel (Fig. 1a). The exposed sedimentary rocks consist of intercalated shale, siltstone, gypsum, dolostone, and limestone beds (Bartov et al., 1972) that dip ~15° to the east. Due to drape-related extension and consequent tilting of the strata, weak shale units throughout the outcrop deformed by an initial phase of flexural slip with a top-to-the-west sense of motion as established by a host of kinematic indicators detailed in Gross et al. (1997). The heterogeneous mechanical stratigraphy resulted in a variety of structural elements confined to individual units at various scales, including bed-parallel shear zones in shales, asymmetrically folded bed-parallel veins, antithetically rotated blocks in competent beds, boudined dolostone beds, and en échelon vein arrays in shales. Both the magnitude and style of deformation was partitioned throughout the section, with simple shear occurring in slip zones and pure shear extension in boudined and veined units (Fig. 1c).

The white gypsum-filled sigmoidal veins stand out by virtue of their abundance and contrast in color with the darker host rock. The west-dipping veins are found in shale beds immediately adjacent to slip zones, and are inclined at an oblique angle to bedding (Fig. 1b). The sigmoidal veins developed as pure opening-mode fractures, as evidenced by a lack of shear offset across the veins and the absence of wall-rock rotation between adjacent veins belonging to the same array. Vein density and aperture in a given bed is directly proportional to intensity of simple shear along adjacent flexural slip horizons as manifested by slip zone thickness and fabric development (Gross et al., 1997). In the absence of nearby bedding plane slip zones, shales are undeformed and do not contain sigmoidal veins. Where slip has occurred within narrow (~0.1–2.0 cm) bedding parallel fault zones, sigmoidal veins developed in nearby shales (Figs. 2a, 3a and b). Where nearby shear zones are well developed, however, veins may constitute over 50% of the rock mass, and sigmoids often merge together to form thick bed-parallel veins (Figs. 2e and 3c). Large differences in slip magnitude along array boundaries resulted in differences in amount of extension, and hence the bed-parallel veins are typically found on only one side of the array (Figs. 2e and 3b). The most intensively developed slip zones increased in thickness by expanding into neighboring

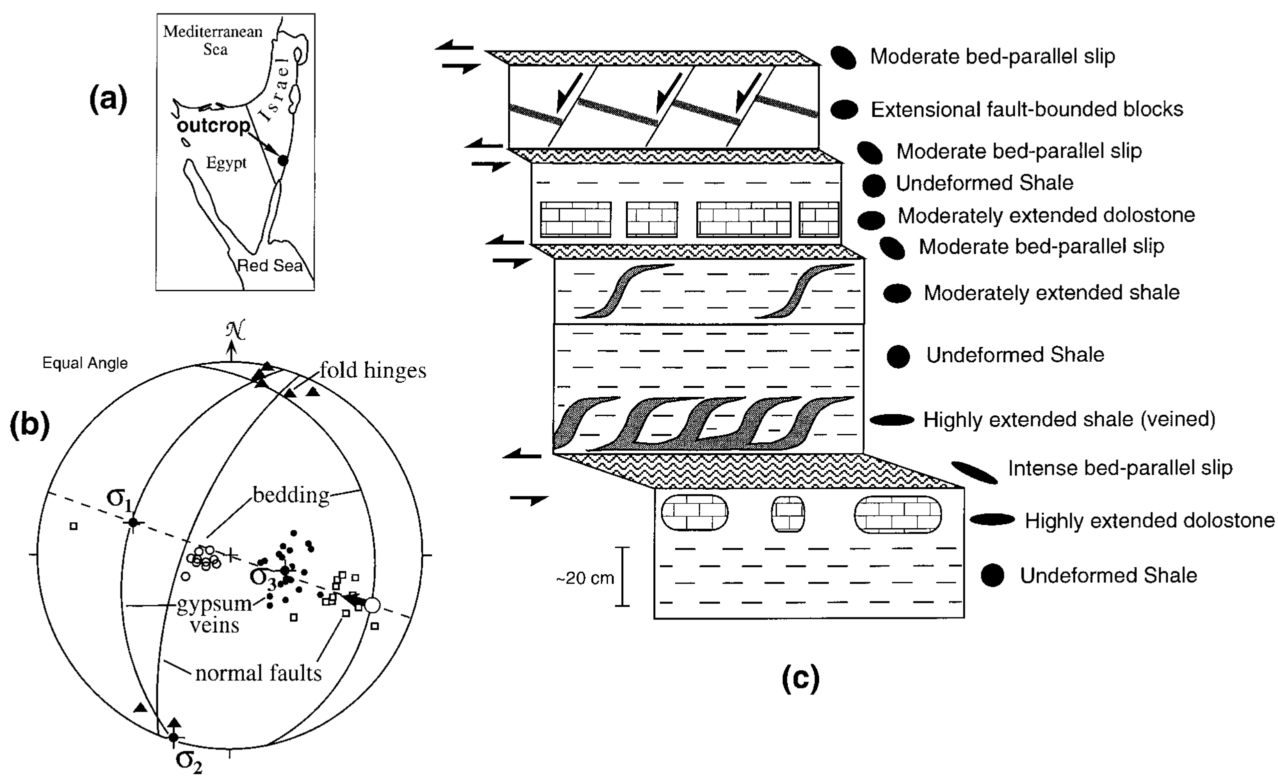

Fig. 1. (a) Location of Ma'aleh Gerofit outcrop; (b) lower hemisphere equal angle projection of structural elements related to bedding plane slip and their kinematics. Arrow with circle is slip vector calculated as intersection between mean bedding and M-plane (dashed great circle) as determined from asymmetric fold hinges and normal faults; (c) variety of structures that developed within the heterogeneous mechanical stratigraphy in response to bedding plane slip. Simple shear localized in shale slip zones resulted in pure shear extension in adjacent units, as manifested by boudins, normal faults, and opening-mode sigmoidal veins. Refer to Gross et al. (1997) for details on relations between mechanical stratigraphy and the flexural slip mechanism at this outcrop.

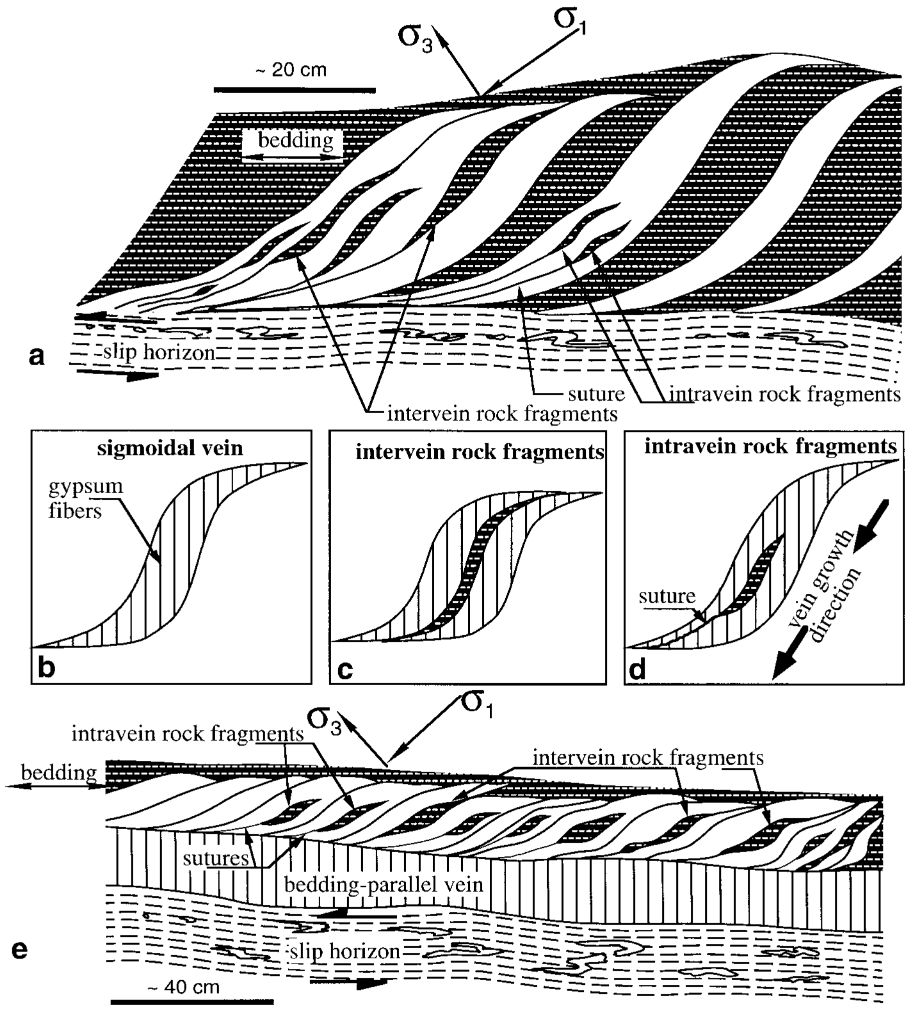

Fig. 2. Sketches of sigmoidal vein geometries and relations to slip zones. (a) Sigmoidal gypsum veins (white) in moderately extended shale bed above a bedding parallel slip zone. Intervein fragments are rock in between separate veins, while intravein fragments are enclosed within one vein. Note that bedding within rock fragments is parallel to overall outcrop bedding. (b) Gypsum vein fibers in isolated veins. Note that individual fibers span from wall to wall. (c) Gypsum fiber arrangement for intervein wall-rock fragments. Note two separate groups of fibers along the entire vein length. (d) Gypsum fiber arrangement for intravein wall-rock fragments. Note that one set of fibers diverges and reconnects as two sets bounded by a medial suture, providing direction of vein growth. (e) Sigmoidal gypsum veins in highly extended beds. Note that most of the bed is comprised of vein material. In all sketches σ_1 and σ_3 arrows are maximum and minimum principal stresses (see text for kinematic explanation). Note they are consistent with movement along slip zones.

beds, in the process incorporating pre-existing sigmoidal veins into the shear zone. These veins were stretched and sheared, and deformed into asymmetric folds identified by shortened forelimbs, boudined backlimbs, and floating hinges.

3. Vein and rock fragment description

The veins are filled with fibrous gypsum and are roughly symmetrical, consisting of a thick inclined central portion that tapers off into narrow tails parallel to bedding (Figs. 2 and 3). Unlike other fibrous veins described in the literature that grow parallel to the direction of maximum extension (e.g. Durney and Ramsay, 1973; Ramsay and Huber, 1983), the gypsum fibers within sigmoidal veins at Ma'aleh Gerofit are aligned vertically irrespective of vein wall orientation. Thus, we infer that fiber growth was controlled by gravity rather than kinematics related to en échelon fracture development, similar to the 'nontectonic cavity growths in veins' described by Durney and Ramsay (1973). The easily deformed gypsum fibers commonly display shear offset adjacent to vein walls as a result of vertical compaction, with a down-dip sense of motion and magnitude proportional to the dip amount of the vein segment.

Individual subparallel veins are aligned en échelon, forming a set of bed-confined arrays whose overall orientation is parallel to bedding. The fissile shale is easily removed from around the veins, providing the opportunity to trace the curvi-planar veins in three dimensions (e.g. Smith, 1995). The veins maintain their sigmoidal shape and en échelon alignment along strike, and do not merge along strike into single parent fractures as is the case for en échelon fringe cracks (e.g. Pollard et al., 1982; Kulander and Dean, 1985; Craddock and van der Pluijm, 1988). Cross-sectional lengths of the inclined central segments are restricted by host shale bed thickness, and range in trace length from ~1 cm to ~2 m.

Of particular interest are the numerous dark shale rock fragments situated between and within the white sigmoidal gypsum veins. The rock fragments are distinguished by three important characteristics: their sigmoidal shape mirrors the shape of enclosing veins, they are aligned in arrays parallel to the overall vein array, and bedding within fragments is parallel to overall outcrop bedding (Figs. 2 and 3).

We divide sigmoidal wall-rock fragments into two main groups: *intervein* fragments that represent host rock in between two separate veins (referred to as

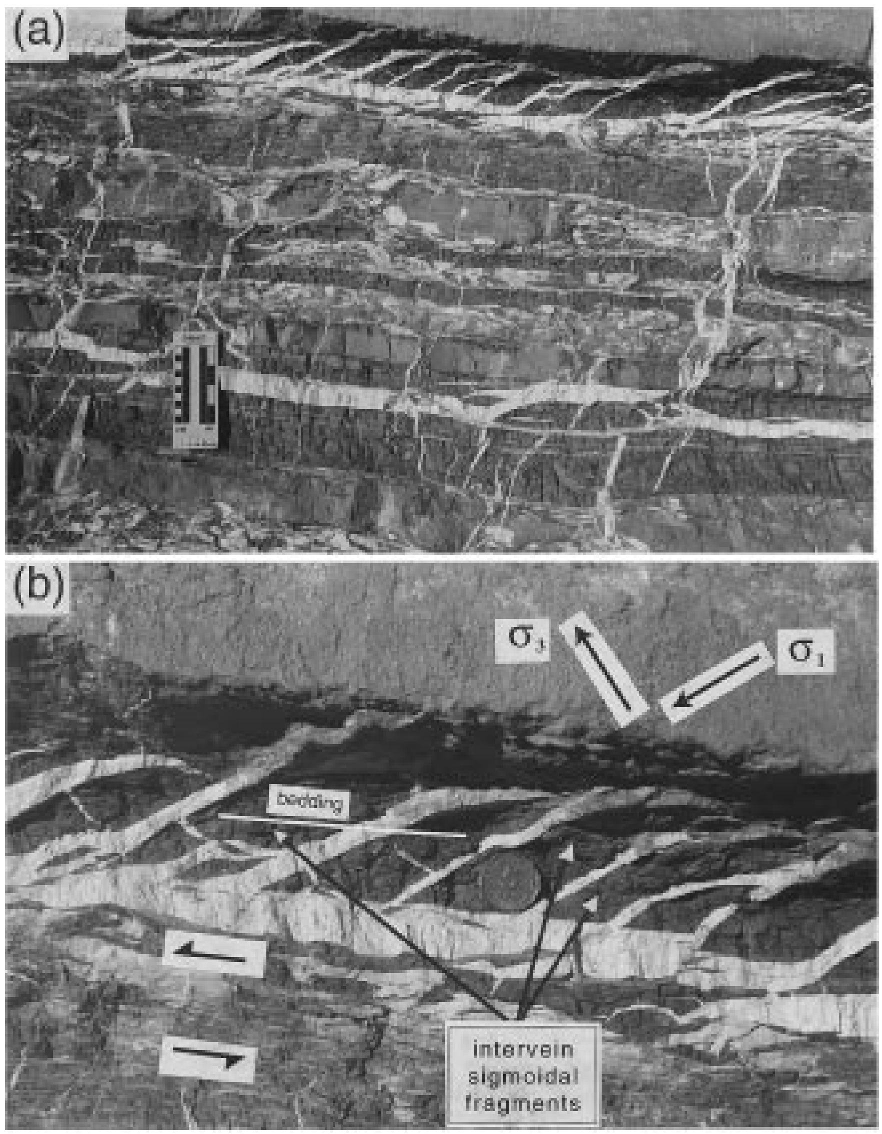

Fig. 3. Photographs of sigmoidal wall-rock fragments within en échelon gypsum vein arrays at Ma'aleh Gerofit, Israel. (a) Overall view of structural elements and fabrics in shale-rich section. Beds dip ~15° to the east (right). (b) Bedding parallel en échelon vein array in moderately extended shale above a flexural slip zone [close-up of top of (a)]. Note sigmoidal-shaped intervein fragments of shale wall-rock in between regularly spaced inclined veins. Bedding within the fragments parallels overall bedding, indicating absence of internal rotation. Coin is 2.4 cm in diameter. (c) Bed-parallel gypsum vein comprised of numerous sigmoidal gypsum veins in highly extended strata above flexural slip zone. Consistently west-dipping sigmoidal wall-rock fragments are enclosed within vein mass. Coin is 1.8 cm in diameter. (d) Close-up of intravein sigmoidal wall-rock fragments. Note in all photos the sigmoidal shape of fragments and their en échelon alignment parallel to overall vein array. Note σ_1 and σ_3 determined from sigmoidal wall-rock fragments. Bedding is indicated by white lines.

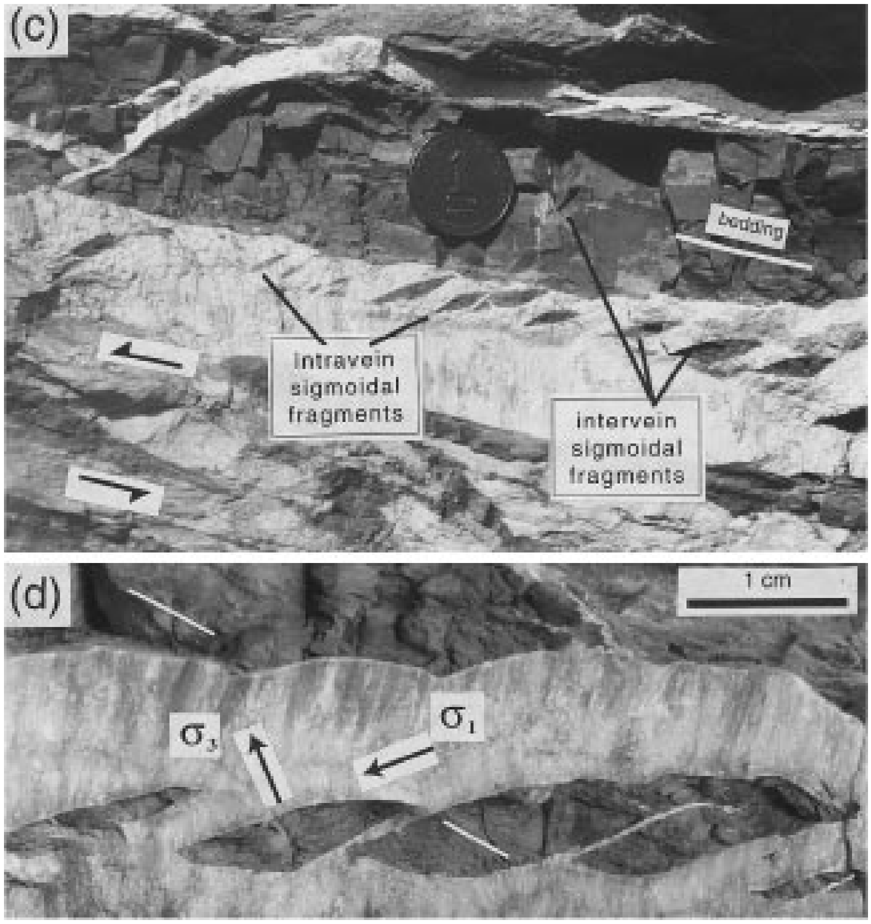

Fig. 3. (*continued*)

'bridges' by Nicholson and Pollard, 1985) and *intravein* wall-rock fragments that are pieces of host rock incorporated into the middle of an individual vein (Figs. 2 and 3). In moderately extended shale beds where veins are more widely spaced, the distinction between the two types is clear: the majority of intervein fragments are approximately equal in dimension to the sigmoidal veins themselves (Fig. 3b), whereas the intravein fragments are considerably smaller and appear as chips enclosed within a mass of gypsum (Fig. 3d). However, in highly extended zones comprised primarily of gypsum, intervein and intravein fragments are often equal in dimension (Figs. 2 and 3c), and the criterion for distinguishing between them is based on vein fiber growth.

Inspection of isolated veins devoid of fragments reveals individual fibers of gypsum that span across the entire vein, implying continuous fiber growth from one vein wall to the other (Fig. 2b). However, veins hosting intravein fragments display a single row of continuous fibers on one side of the fragment, yet two rows of fibers separated by a medial suture on the other side (Fig. 2d). Such a geometry indicates the vein originally grew as a single fracture as manifested by continuous fiber growth from wall to wall, and then split into two segments around the rock fragment with separate continuous fiber growth in each segment. The two vein segments ultimately merged back into a single segment on the opposite end of the wall-rock fragment, though fiber growth remained separate, creating a medial suture where fibers growing from opposing walls met in the center of the vein. In contrast, intervein fragments enclosed within gypsum have medial sutures on both sides, and thus mark the boundary between overlapping veins that originated and grew as two separate fractures (Fig. 2c). In light of their different geometries and origins, we refer to sutures related to intravein fragments as 'internal' and sutures that separate overlapping veins as 'external'.

In several highly extended beds numerous sigmoidal veins overlap in direct contact with each other, forming tabular masses of gypsum that appear as thick bed-parallel veins. Close inspection reveals a series of overlapping sigmoidal vein tails outlined by external suture zones, as well as numerous small intravein and intervein rock fragments aligned en échelon parallel to the overall vein array (Figs. 2e, 3c and d).

4. Discussion and conclusions

4.1. Mechanism of en échelon vein formation

The mechanism responsible for en échelon vein formation at Ma'aleh Gerofit is unambiguous due to excellent three-dimensional vein exposure, primary sedimentary fabrics that prove absence of rotation between and within veins, and a host of kinematic indicators and fabrics found throughout the outcrop (Fig. 1). The kinematics are constrained by two key factors: the en échelon sigmoidal veins initiated and grew as pure opening-mode fractures, and they developed in response to and in conjunction with simple shear along bed-parallel slip zones. The latter is based on the observations that (1) vein arrays are present only in beds adjacent to slip zones, (2) intensity of vein development is directly proportional to magnitude of slip along adjacent flexural slip horizons, (3) veins are deformed and incorporated into slip zones as the latter expanded in thickness, and (4) the orientation of principal stresses derived from the opening-mode veins is consistent with the stress configuration during flexural slip.

Opening-mode fractures grow perpendicular to the local least principal stress (σ_3) and in the plane containing the local intermediate (σ_2) and maximum (σ_1) principal stresses (Dyer, 1988; Pollard and Aydin, 1988). Bedding within both intravein and intervein fragments is parallel to the overall bedding outside the vein arrays, demonstrating a lack of internal rotation between adjacent veins. Thus, the sigmoidal veins at Ma'aleh Gerofit grew as curved opening-mode cracks in a manner similar to the 'curving-parallel geometry' described by Dyer (1988), whereby fracture curvature results from local stress perturbations in the vicinity of a planar discontinuity (in this case bed partings), rather than due to incremental rotation of vein segments within a simple shear zone. Consequently, σ_3 that prevailed during vein formation is perpendicular to the planar central portion of the vein (Figs. 1b and 4), while σ_1 and σ_2 fall within the plane of the central vein segment, though their precise alignment cannot be determined by the veins alone. However, top to the west bedding plane slip requires that σ_1 and σ_3 fall within the movement (M-) plane (Goldstein and Marshak, 1988), which is oriented normal to bedding and contains the slip vector (Figs. 1b and 4). Polished slickensides, and hence fault striae, are not preserved within and in contact with shear zones due to fissility of the shale. Thus, the M-plane was determined from other structural elements, namely antithetically-rotated blocks in competent beds and sheared veins. An average M-plane was calculated as the plane perpendicular to asymmetrical fold hinges within slip zones and perpendicular to normal fault surfaces (Figs. 1b and 4). The slip vector is then estimated as the intersection between bedding and the M-plane. Note that σ_3 calculated from the sigmoidal veins falls precisely along the

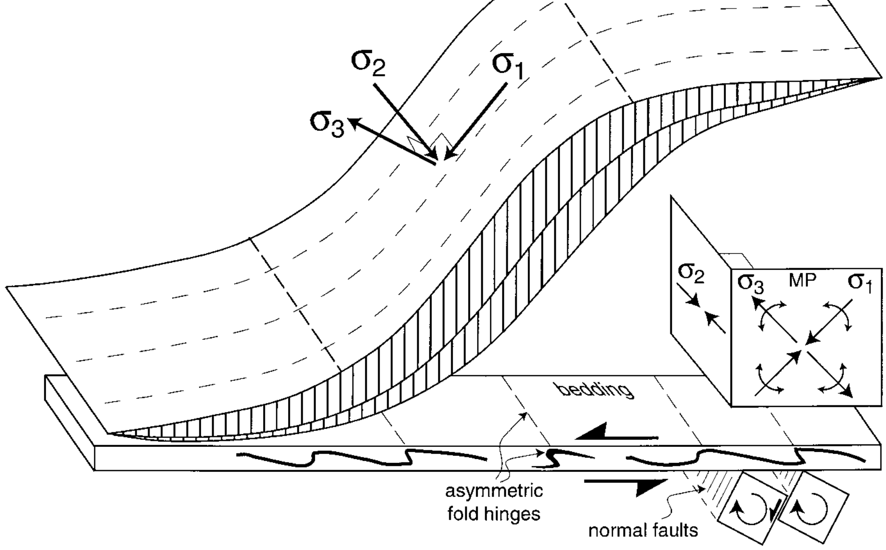

Fig. 4. Derivation of principal stresses from sigmoidal veins and fabrics related to bedding plane slip. Opening-mode veins constrain σ_3, which falls within the movement plane (MP), thus constraining σ_1 and consequently σ_2. Refer to text for more detail.

M-plane. This constrains σ_1, which must also lie on the M-plane at 90° from σ_3, thus constraining σ_2 which by definition is mutually perpendicular to the other two principal stresses. The facts that (1) σ_1 and σ_2 fall along the great circle of mean vein orientation, (2) σ_2 resides within the cluster of fold hinges, and (3) σ_3 determined from opening-mode veins falls along the M-plane all demonstrate that the sigmoidal veins are genetically and kinematically related to the slip zones: clearly the opening-mode sigmoidal veins grew in response to applied simple shear along array (bed) boundaries. We emphasize that whereas the mechanism for en échelon vein development is simple shear along bed boundaries external to the vein array, the actual zone of rock comprised of en échelon veins is deformed under pure shear extension (Figs. 1c, 2a, e, 3b, c, 4 and Fig. 5).

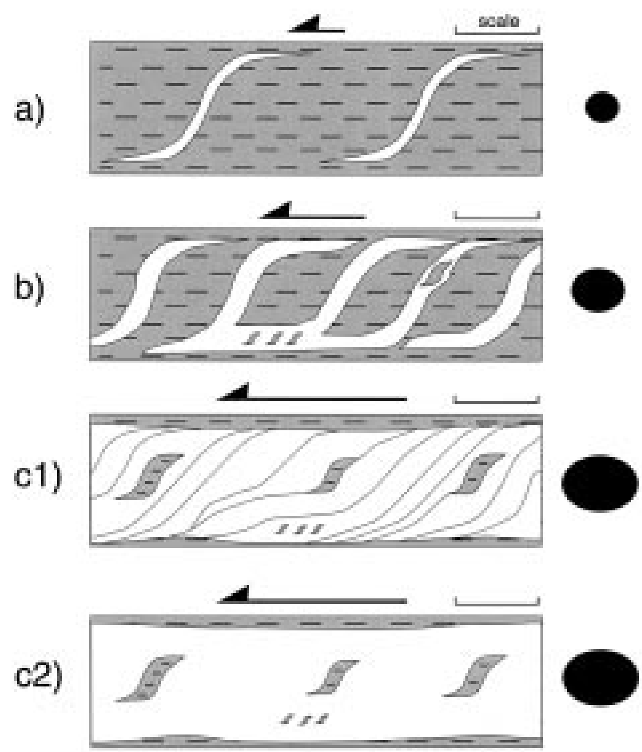

Fig. 5. Sequential extension/dilation and development of gypsum vein arrays due to increasing simple shear strain (as indicated by increasing arrow length) in adjacent slip zones. (a) Widely spaced thin sigmoidal veins in slightly extended shale beds. (b) Moderately extended beds with evenly spaced veins. Note sigmoidal shape of intervein fragments between veins, and smaller sigmoidal intravein fragments within individual veins. (c1) High amounts of extension parallel and perpendicular to bedding lead to unit comprised primarily of vein material, forming a large tabular vein complex parallel to bedding. Note that sigmoidal rock fragments and vein boundaries serve as remnants of original en échelon vein array. (c2) Same as c1, except that vein boundaries are not readily apparent. Sigmoidal vein fragments are only indicators of vein array and simple shear zone. Strain ellipses depict extension and dilation. Relative scale is uniform throughout.

Furthermore, the direction of vein growth can be determined from intravein medial sutures because a vein with continuous fibers rejoins as two separate rows of fibers upon diverging around the rock fragment (Fig. 2d). Progressive development of the en échelon vein array may eventually lead to a large, tabular body composed primarily of vein material interspersed with numerous small sigmoidal wall-rock fragments, yet without any trace of the original sigmoidal vein geometry (Fig. 5).

4.2. Rock fragments as kinematic, stress orientation, and vein orientation indicators

In cases where vein arrays formed in association with simple shear, wall-rock fragments may be used as kinematic indicators of the shear zone in the same manner as sigmoidal veins (Fig. 6). This is because the shape of the rock fragments precisely reflects sigmoidal vein shape. As is the case for sigmoidal veins (e.g. Ramsay and Huber, 1983, 1987) the technique may be applied whether or not internal wall-rock rotation occurred, however one must always establish a direct correlation between en échelon vein development and simple shear motion. The advantage of using sigmoidal rock fragments as kinematic indicators occurs where vein geometry is not attainable or delineated. For example, the external boundaries of a large vein may not be exposed, yet abundant small rock fragments within the vein may provide kinematic information if they are sigmoidal and consistent in orientation (e.g. Figs. 3d and 5c). Identifying the numerous veinlets that comprise a massive stockwork may also be impossible, thus sigmoidal wall-rock fragments may provide the only recourse for establishing kinematics.

Where internal rotation has not occurred, such as the examples presented in this study, wall-rock fragments may additionally serve as indicators of stress and vein array orientation. The absence of wall-rock rotation is easily confirmed by comparing the orientation of any pre-existing fabric (e.g. bedding, foliation, lineation, aligned phenocrysts in intrusive rocks) within wall-rock fragments to the same fabric outside the vein system. If the fabrics are aligned parallel to each other, then by virtue of their similarity in shape to sigmoidal veins, the least principal stress is perpendicular to the central segment of the wall-rock fragment, and maximum principal stress is in the plane parallel to the central segment (Figs. 1, 2 and 6). Furthermore, the along-strike continuation of the vein array may be predicted on the basis of unrotated sigmoidal rock fragments, whose tails are aligned parallel to the boundary between the vein array and country rock (Fig. 6a). Where internal rotation has occurred, only the sense of shear can be determined from the rock fragments (Fig. 6b).

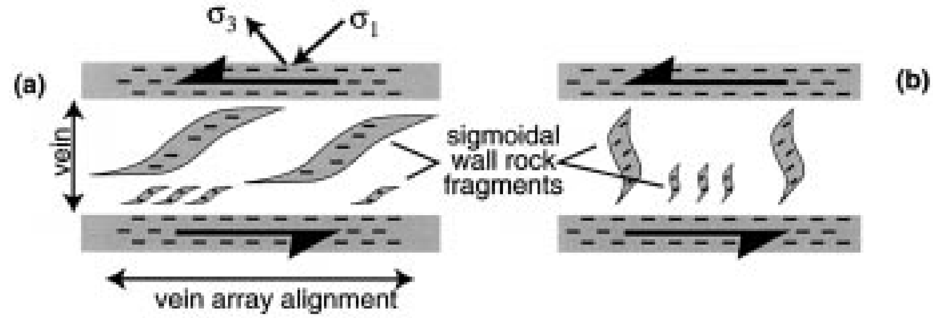

Fig. 6. Sigmoidal wall-rock fragments as kinematic indicators within en échelon vein arrays. (a) Unrotated wall-rock fragments. (b) Rotated wall-rock fragments. Note that principal stress orientations and alignment of vein array may be determined in the absence of internal rotation. Sketches are scale independent.

In summary, the unique shape and alignment of sigmoidal wall-rock fragments may shed light on the origin of en échelon veins, and may serve as important kinematic indicators and indicators of vein array orientation. One application of this new kinematic indicator is in mining exploration and development, where large vein complexes are only partially exposed and thus geometries and dimensions of the veins and arrays are not easily constrained. In these cases sigmoidal rock fragments may shed light on the trends of massive veins and arrays, and may identify potential ore bodies on the basis of kinematics and structural geometry.

Acknowledgements

We thank Emanuel Mazor of the Ramon Science Center (Israel), Gabriel Gutiérrez-Alonso, and Scott Wilkins for field assistance and helpful discussions. This study was supported by United States–Israel Binational Science Foundation Grant No. 94-00396 and by a grant from the Florida International University Foundation. We thank John Craddock, James Evans, and Gregory Ohlmacher for helpful comments.

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