TECTONICS, VOL. 2, NO. 2, PAGES 167-185, APRIL 1983

TECTONIC ANALYSIS OF THE DEAD SEA RIFT REGION SINCE THE LATE-CRETACEOUS BASED ON MESOSTRUCTURES

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Abstract. We have measured the orientations of small faults, slickensides, tectonic stylolites, vein with secondary mineralization, small folds and dikes in Israel and Sinai. These structures are indicators of paleo-stress or strain and provide the pattern of tectonic deformation. Data were collected at 130 stations, most with tens of separate measurements; most stations showed consistent deformation. Stations were located on exposures ranging from Precambrian crystalline rocks to Pleistocene sediments. We have defined two tectonic stress fields, each relatively uniform in both time and space. One stress field, with dominating maximum horizontal compression trending W to WNW, in the Late Cretaceous to Eocene rocks in the folds and plateaus west of the Dead Sea rift. The second field, with dominating horizontal extension trending E to ENE, in all rocks inside the rift and proximal thereto. The first stress field is called the Syrian Arc stress, and the second is called the Dead Sea stress. A change in style of tectonic deformation, which corresponds to the two stress fields, is manifested also in the major structures in Israel. The Late Cretaceous to Neogene deformation is characterized by long wavelength folds and monoclines, whereas the Neogene to Recent deformation is characterized by normal and strike slip faults and volcanic activity.

INTRODUCTION

The tectonic history of the Sinai - Israel subplate since the Cretaceous is investigated here through a study of mesostructures. The measured mesostructures, mostly small faults, tectonic stylolites and veins, are relatively accurate indicators of the strain orientation. By determining the local strain in many stations, we construct regional strain fields for a few periods. These fields permit elucidation of a tectonic history that is both independent of and complementary to the history revealed by the macrostructures. We consider here macrostructures as structures shown on geologic maps, mesostructures as structures seen from hand specimen size to an exposure size, and microstructures as structures seen under the microscope.

Commonly the strain deduced from mesostructures is consistent with the strain deduced from the host macrostructures [e.g., Wartolowska, 1972; Hancock and Atiya, 1979; Reches et al., 1981]; However, it has been shown that the two

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Paper number 3T0238.
0278-7407/83/003T-0238$10.00

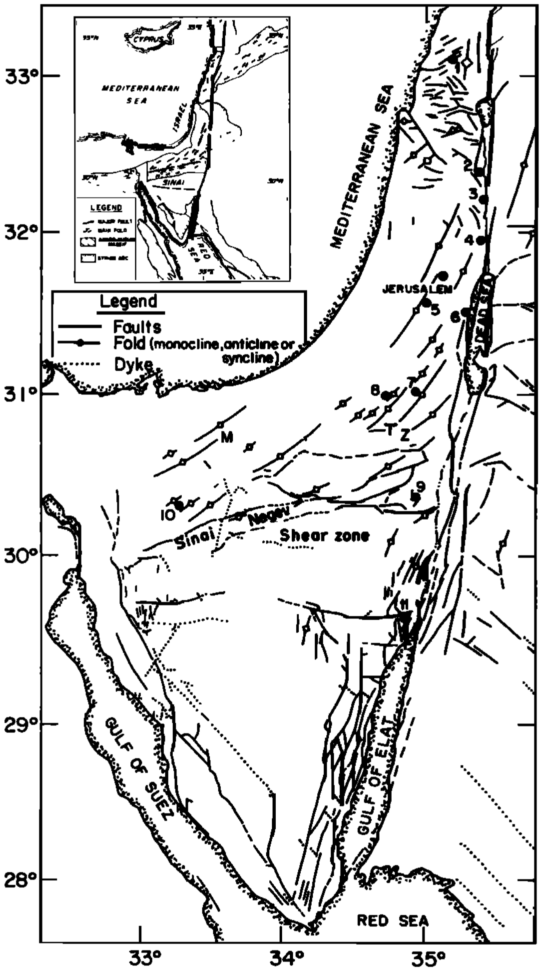

Fig. 1. A generalized tectonic map of Israel - Sinai subplate (after Bartov [1974] and Freund and Rozenberg [1978]). Eleven selected stations are marked.

strains may differ [e.g., Reches, 1978; Groshong et al., 1978]. For example, Reches [1976] showed that small faults in southern Israel, indicate sub-horizontal compression oriented W to WNW. These small faults were measured within two large monoclines that trend toward the NE, thus indicating compression in a NW direction. This last direction deviates by 25° to 45° from the direction of the shortening associated with the small faults. Similar deviations were found in our field work and are discussed in the present study.

Tectonic Setting

The Sinai - Israel subplate is bounded by the Dead Sea rift on the east and by the Gulf of Suez on the southwest (Figure 1). The regional tectonics has been studied through the analysis of folds and monoclines of the Syrian Arc system, major unconformities, and large fault systems [e.g., Picard, 1943; Bentor and Vroman, 1954; de Sitter, 1962; Freund, 1965; Garfunkel, 1970; Bartov, 1974; Freund et al., 1975; Eyal et al., 1981]. During the last two decades the tectonic deformation of the subplate has been attributed to the motion of the bounding African and Arabian plates [e.g., Quennell, 1959; Freund, 1965].

Located on the margins of the Arabo-Nubian massif (Figure 1), the Sinai - Israel region is covered by a sequence of shallow marine and continental sedimentary rocks. The sequence, which is up to 12 km thick, includes arkoses, sandstones, limestones, dolomites, marls, and evaporites. A basement of igneous and metamorphic rocks of Pre-Cambrian to Early-Cambrian age underlies the sedimentary rocks. The Sinai - Israel region underwent relatively gentle deformation since the Triassic. The regional structures are major faults and open folds that formed under low temperature and low pressure conditions. The main mechanism of small scale deformation include pressure solution, calcite twinning, and the formation of mesostructures. These deformation features are the subject of the present work.

We first describe our present and previous [Eyal and Reches, 1979] field measurements. Then we discuss the relationship of mesostructures and their host macrostructures. Finally, a tectonic history for the Sinai - Israel subplate since the Late Cretaceous is presented.

STRAIN ANALYSIS

Field Measurements

The orientation of the strain field was determined by field measurements of mesostructures with clear sense of displacement. Joints, which usually lack evidence of displacement, were not measured in spite of their abundance. We examined many natural and artificial exposures and established a station at each site with enough suitable mesostructures. About 130 stations are distributed in Israel, the Dead Sea rift, and in the Sinai Peninsula. Three types of mesostructures were commonly measured: tectonic stylolites, small faults (with slickensides) and veins (Figure 2).

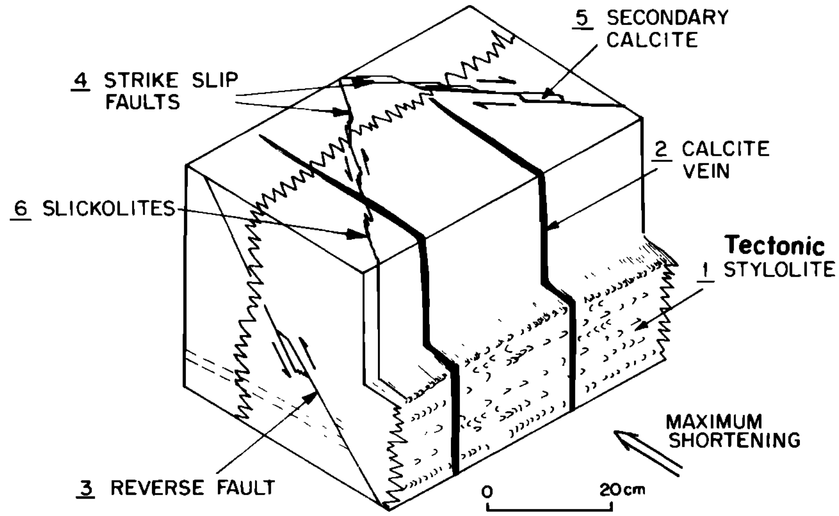

Fig. 2. Schematic presentation of the measured mesostructures. E_1 indicates the maximum compressive axis.

Tectonic Stylolites. Stylolites are serrated surfaces with interlocking columns that are usually coated by clay seams. Stylolites may occur in many rock types but are particularly common in limestones and are believed to be the product of pressure solution under non-hydrostatic stresses. Usually, the columns of stylolites are either sub-normal or sub-parallel to bedding. The first type are usually considered to form by the overburden load and are called sedimentary stylolites. The second type are considered to form due to tectonic stresses and are called tectonic stylolites [e.g., Choukroune, 1969]. In a few special cases, however, stylolites of the first type may be of tectonic origin. Tectonic stylolites may develop freshly in massive rock or may serrate preexisting planes such as joints, faults [Wartolowska, 1972; Hancock and Atyia, 1979] or mud-cracks. We measured the orientation of the columns of tectonic stylolites as it is generally accepted that this direction represents the direction of maximum compression [e.g., Choukroune, 1969].

Small Faults. Small faults with clear indication of the sense of displacement were measured. We usually determine this sense by slickensides and slickolites. Slickolites are the combination of slickensides and stylolites; they develop where local pressure solution occurs due to irregularities of the fault surface. The sense of displacement was also determined by secondary mineralization filling rhomb-shaped holes along irregular fault surface (Figure 2) [e.g., Marshak et al, 1983], and by stratigraphic separation.

Veins. Veins with secondary mineralization occur in many outcrops in the study area. Calcite has been found in the common filling, but gypsum and clay have also been found. Commonly, veins are associated with tectonic stylolites; in these cases the columns of the latter parallel the vein surface (Figure 2). This relationship between the filled veins and the columns of the tectonic stylolites suggests that calcite that was removed by pressure solution from the stylolites was redeposited in the veins. The stylolite-calcite vein relationship vary; veins are cut and displaced by stylolites or veins terminate against stylolites or veins cut across stylolites. We have also measured the orientation of a few igneous dikes in the Galilee and Sinai.

The orientation data of the mesostructures measured at a station were projected onto an equal area stereonet. The mean and standard deviation of the various sets were calculated according to Fisher [1953]. The results from stations in which the beds are inclined were retilted by rotation around the strike. Columns of tectonic stylolites indicate the compression axes and normals to filled veins and igneous dikes indicate extension axes. The principal compression and extension axes associated with a small fault are taken as the bisectors between the normal to the fault and the slip direction (slickenside or slickolite striations). When a conju-

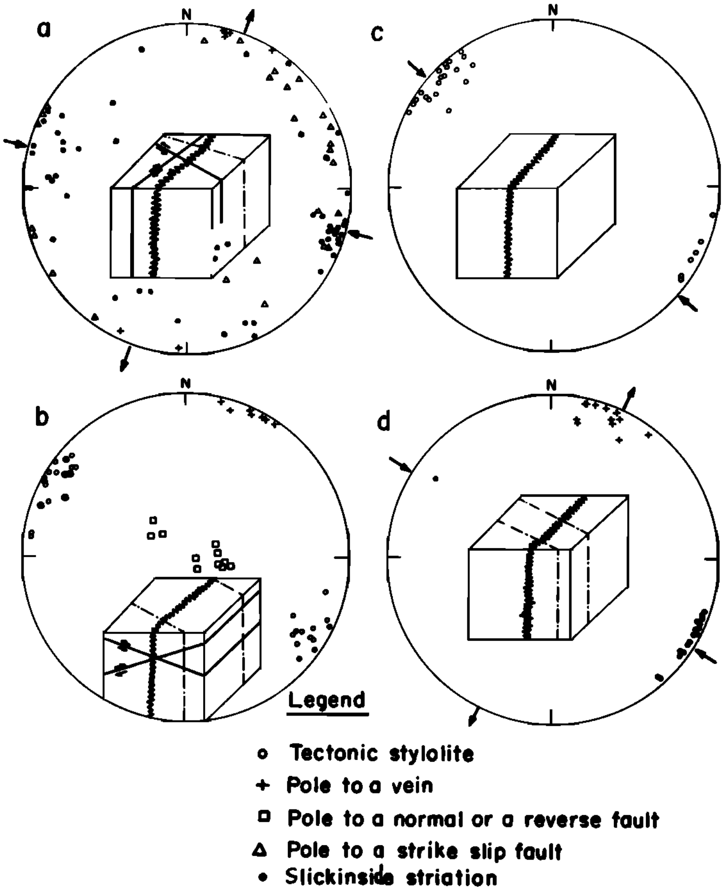

Fig. 3. The orientations of the mesostructures of the Syrian-Arc strain (see text). Retilted orientations; equal area, lower hemisphere projection. Station locations in Figure 1. (a) Station 1, Nahal Matat, Cenomanian limestone (from H. Ron and Y. Eyal, manuscript in preparation, 1983) (b) Station 5, Haras, Turonian limestone. (c) Station 6, Nahal Deragot, Cenomanian dolomite. (d) Station 9, Meishar, Eocene limestone.

gate set of faults occurs, the principal axes are the bisectors of the angles between the two fault sets. The simple fault patterns observed here (see below), make it unnecessary or even impossible to use recent methods of stress inversion [e.g., Angelier, 1979; Armijo et al., 1982]. The orientation of the principal strain axes of a station are the mean orientations of the axes of the individual mesostructures.

Results

The present analysis of the mesostructures in the Sinai - Israel subplate reveals consistent strain patterns from the scale of a single station (Figures 3 and 4), to the regional scale (Figures 6 and 9). We identified two separate tectonic regions by these strain patterns; the Dead Sea rift and the subplate itself. We also recognize the age of the tectonic phases by using stratigraphic criteria and ages of igneous intrusions.

Local Strain. In a single station the strain associated with the different mesostructures appears to be consistent (Figures 3 and 4). For example in station 9 (Figure 3d) the compressive axis determined from tectonic stylolites, 1°/118°±7°, is perpendicular to the extension axes determined from calcite veins, 6°/021°±12°. A similar situation, although with different orientations, is shown in Figure 4d. Here, the compression axis determined from tectonic stylolites is 2°/344°±11°, whereas the extension axis

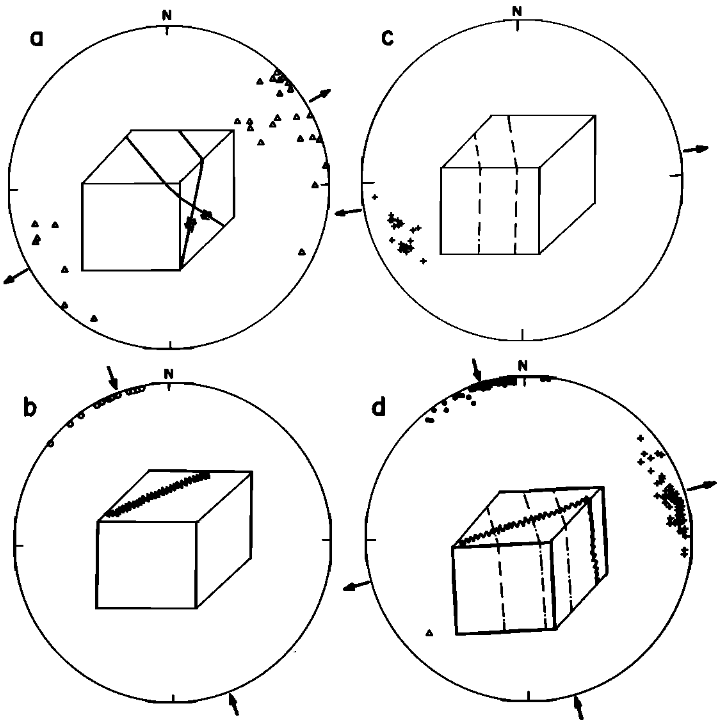

Fig. 4. The orientation of the mesostructures of the Dead-Sea Strain (see text). Retilted orientation; equal area, lower hemisphere projection. Station locations in Figure 1. Legend in Figure 3. (a) Station 3, Mifgash Habikaa, Pleistocene marl. (b) Station 7, Yeruham, Miocene limestone. (c) Station 10, Gebel Minshara, Lower Cretaceous limestone. (d) Station 11, Nahal Netafim, Cenomanian limestone.

determined from calcite veins is 6°/077°±11°. In station 5, we measured two sets of reverse faults, tectonic stylolites and calcite veins (Figure 3b). In this station, the compression axis plunges 4°/115° according to the reverse faults, or 2°/301°±12° according to the tectonic stylolites; an extension axis oriented 6°/025°±9° was determined from the calcite veins. Similar apparent correspondence of the strain axes determined from different mesostructures was observed at most stations (Figures 4 and 5).

In most stations two of the principal axes of the strain are sub-parallel to the local bedding, whereas the third one is sub-normal to it. Thus, the principal axes become sub-horizontal and sub-vertical after retilting (Figures 3, 4, and 5). We consider the sub-vertical axis as reflecting local overburden, whereas the sub-horizontal axes are attributed to tectonic deformation.

A few stations depart from the simple pattern of Figures 3 and 4. For example, two axes of compression with different orientations may be determined (Figure 5a). Or, an extension axis and a shortening axis that are not mutually perpendicular are determined (Figure 5b). We interpret the occurrence of two non-corresponding deformation axes as reflecting two tectonic phases that have deformed the same locality, during different periods.

The range of mesostructures is not equally distributed between stations. In station 6 (Figure 3c), only tectonic stylolites were found, and thus only the compression axis could be determined. Or, in station 10 (Figure 4c) where filled veins prevail, only the extension axis could be determined. According to the type of the prevailing structure, we recognize stations and periods of dominating compression or extension.

Areal Strain. The strain axes determined in several stations from the same area also show consistent patterns (Figures 6, 7, 8, 9, and 10). For example,

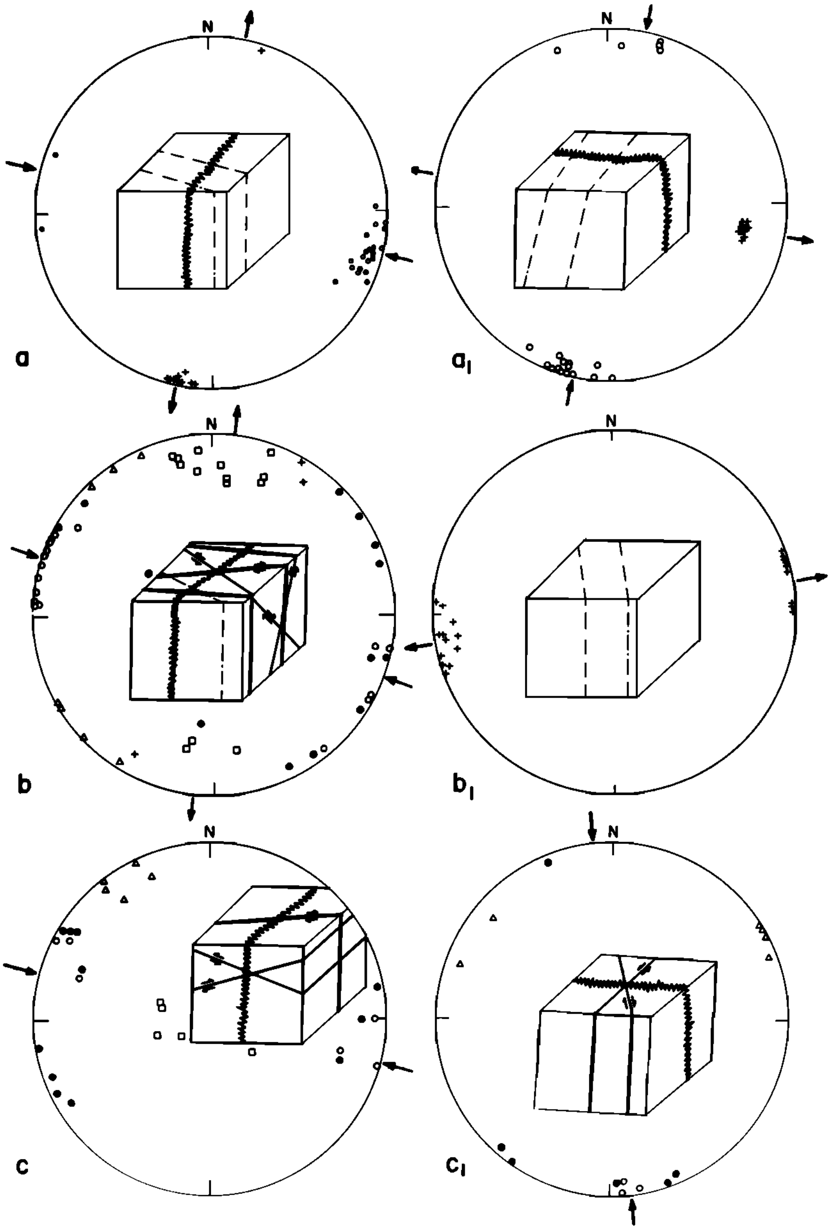

Fig. 5. The orientation of the mesostructures in stations with two strains in each; an older on the left, and a younger on the right (see text). Retilted orientations; equal area, lower hemisphere projection. Station locations in Figure 1. Legend in Figure 3. (a) Station 2, Wadi Malih, Jurassic limestone. (b) Station 4, Naaran, Eocene limestone. (c) Station 8, Boquer anticline, Turonian limestone.

in the Jerusalem - Hebron area, which extends for about 35 km west of the Dead Sea, the mean compression axis is horizontal, trending 297°, and the mean extension axis is horizontal, trending 026° [Eyal and Reches, 1979; Reches et al., 1981]. Similar relationships have been found in the central and western Galilee [Ron and Eyal, 1981], the northern Negev [Reches, 1976], Jordan Valley, northern Sinai and Elat regions (see Figures 6, 7, 8, 9, and 10).

The retilting of the strain axis at each station by rotation about the local strike, brings all stations in an area to a common datum. The axis from gently dipping layers are only slightly modified by this retilting. This operation tests the relative age of mesostructures in steeply dipping layers. For example, strain axes of steep layers in the Syrian Arc system were modified by retilting to have closer orientations to axes of gently dipping layers [see also Reches, 1976; Reches et al., 1981].

Regional Strain. The regional strain field shows a surprisingly consistent pattern over large distances. In Figure 7 the compression and extension axes determined from mesostructures are shown together, regardless of location and age. The subvertical axis of the overburden is not shown in this diagram. The dominating trends are (1) compression in W to WNW direction, mean $287^\circ \pm 3^\circ$ with a secondary corresponding extension in N to the NNE direction, mean $017^\circ \pm 4^\circ$ and (2) extension in ENE to E direction, mean $078^\circ \pm 6^\circ$ with a secondary compression in NNW to N direction, mean $345^\circ \pm 5^\circ$.

Four regional types of deformation are recognized:

1. The Israel - Sinai subplate west of the Dead Sea rift is characterized by a consistent compression in W to NNW direction and an associated orthogonal extension (Figure 8). These trends occur in rocks of Cretaceous to Eocene ages. There are some local variations of this strain: Compression prevails and extension is secondary from the northern Negev to the Galilee, whereas extension prevails and compression is secondary south of the Sinai - Negev shear zone. (Figures 8 and 10). As most stations that underwent compression in W to WNW direction are located within the Syrian Arc system (Figures 1 and 10), we call this strain the 'Syrian Arc strain.'

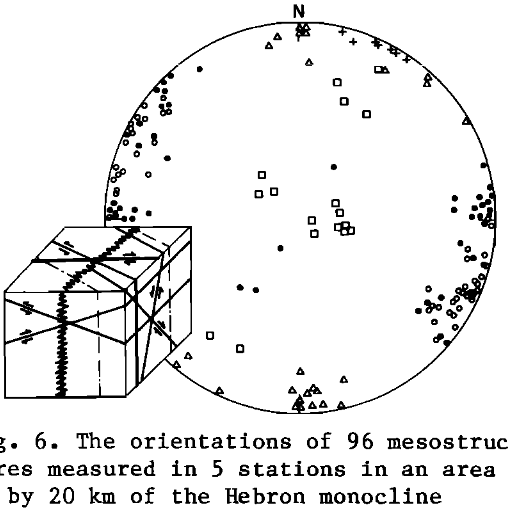

Fig. 6. The orientations of 96 mesostructures measured in 5 stations in an area of 35 by 20 km of the Hebron monocline (proximity of station 5 Fig. 1). Inclined beds were retilted. legend in Fig. 3.

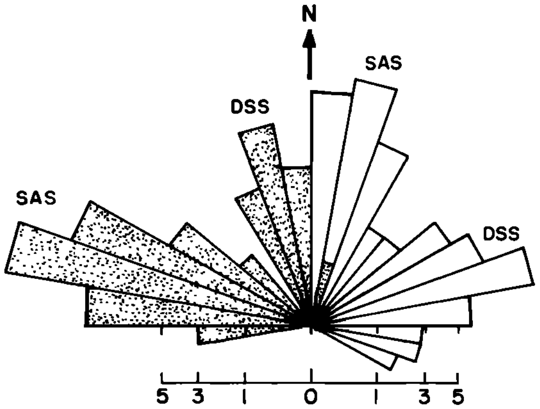

Fig. 7. Rose diagram of the strain axes on a regional scale. Each station is represented by one or two principal axes which are sub-horizontal; sub-vertical axes are not plotted here. Dotted sections are compressive axes, empty sections are extension axes. Data from the Galilee is in part after Ron (unpublished) and Ron and Y. Eyal (1981). Projection of strain axes in all stations divided into the Syrian-Arc Strain (SAS) and the Dead Sea Strain (DSS) (see text).

2. The Dead Sea rift is characterized by ENE extension with an associated NNW compression (Figures 9 and 10). This strain, which we call the 'Dead Sea strain' occurs in rocks and sediments from crystalline Precambrian through Cambrian sandstones to Late Pleistocene marls, mostly within the rift. However, some stations, as far as 170 km west of the rift also show evidence of this strain (Figure 10). The Dead Sea strain was measured in layers with mean dip of $9^\circ \pm 11^\circ$. Therefore, modification of strain orientation due to retilting is negligible.

3. Several stations exhibit two distinct strains. For example, stations in Cretaceous rocks that are close to or within the Dead Sea rift (stations 2 and 8 in Figure 5).

4. A few stations along the west of the Dead Sea rift exhibit a scattered distri-

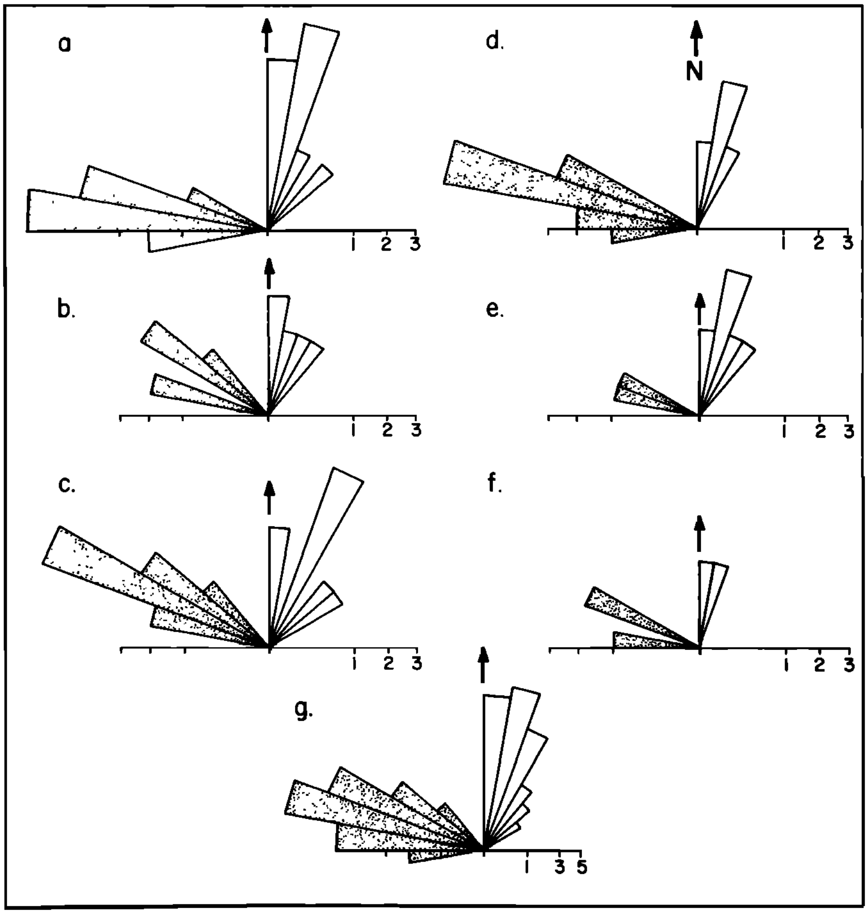

Fig. 8. Same as Figure 7. Projections of strain axes of the Syrian Arc field in six subregions. (a) Galilee; 27 axes. (b) Jordan Valley; 11 axes. (c) Hebron monocline; 23 axes. (d) Northern Negev; 20 axes. (e) Northern Sinai; 8 axes.(f) South Eastern Sinai - Elat; 5 axes. (g) Total of Syrian-Arc axes. For locations of the subregions see Figure 10.

bution of compression axes between NNW and WNW (Figures 3c and 10). These compression axes roughly span the range of the compression axes of the Dead Sea strain and the Syrian Arc strain. As most of these stations are located between the subplate and the rift, we regard this region of scattered distributions, as a transition zone between the subplate and the rift.

Age. The age of the tectonic phases associated with mesostructures may be deduced from the age of the host rock, age of dikes and periods of deformation of large structures. The Syrian Arc strain is associated in location, orientation, and compressive character with the folds and monoclines of the region (Figures 1 and 10). Reches [1976] indicated that Senonian sediments in one monocline in the Negev, were deposited into erosional channels in Turonian rocks. The trends of these channels are controlled by small faults that belong to the Syrian Arc strain system. This relationship indicates that some small faults formed during early stages of the Syrian Arc folding, namely, as early as the Turonian - Senonian period. The youngest rocks that exhibit Syrian Arc type mesostructures are of Eocene age. Schulmann [1981], however, reported two prevailing trends of dikes of Miocene and Pliocene ages in northern Israel: WNW and NNE. The first trend is parallel to and compatible with the maximum compressive axis of the Syrian Arc strain. It is possible, therefore, that the Syrian Arc strain continued even during the Miocene - Pliocene period. We cannot correlate the

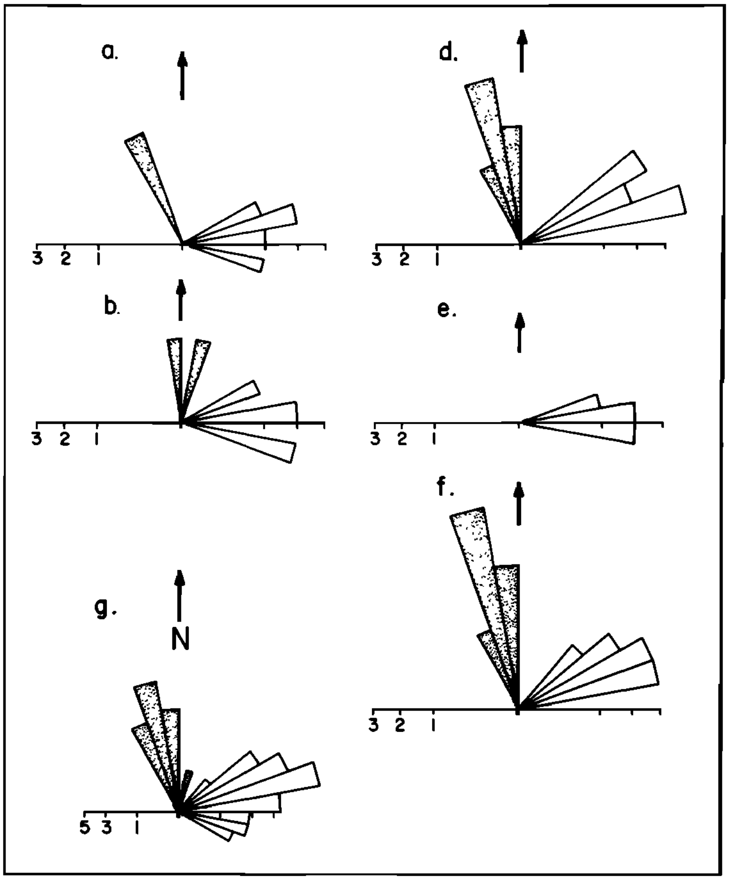

Fig. 9. Same as Figure 7. Projection of strain axes of the Dead Sea field in six subregions. The order of the sub-regions is the same as in Figure 8, except that the Hebron monocline given in Figure 8c is not represented because of lack of relevant data.

second set of dikes with any of the mesostructures.

The Turonian to Neogene time span has been recognized for many years as the main period of development of the large folds and monoclines of the Syrian Arc in Sinai and Israel (Figure 12) [e.g., Picard, 1943; Bentor and Vroman, 1954; de Sitter, 1962; Freund, 1965; Bartov, 1974]. We therefore conclude that the mesostructures also developed during this period.

Several stations in central and northern Israel include evidence for the relative age of the Syrian Arc and the Dead Sea strain fields. In these stations one observes two sets of slickenside striations on small faults that are steeply inclined towards the NE or SW. The older set of striations indicates strike slip motion of Syrian Arc strain, which is obliterated by a younger set indicating normal faulting of the Dead Sea strain.

The time of the onset of the Dead Sea strain is not clear. We assume that it started at the same time as the shear along the rift, namely, after Early Miocene [Eyal et al., 1981; see discussion]. We found evidence for this strain field in rocks and sediments ranging in age from Precambrian to Late Pleistocene. Zak and Freund [1966] and Reches and Hoexter [1981] found mesostructures in Holocene sediments within the Dead Sea rift, which indicate the continuity of the Dead Sea strain into the Holocene. Furthermore, in situ stress measurements in the copper mine of Timna, Dead Sea rift, Elat region, revealed the following stresses: σ_1 - vertical, σ_2 - subhorizontal, trending N15°W, and σ_3 - subhorizontal, trending N75°E [Denekamp and Tzur-Lavie, 1977]. The principal area of the present day stress

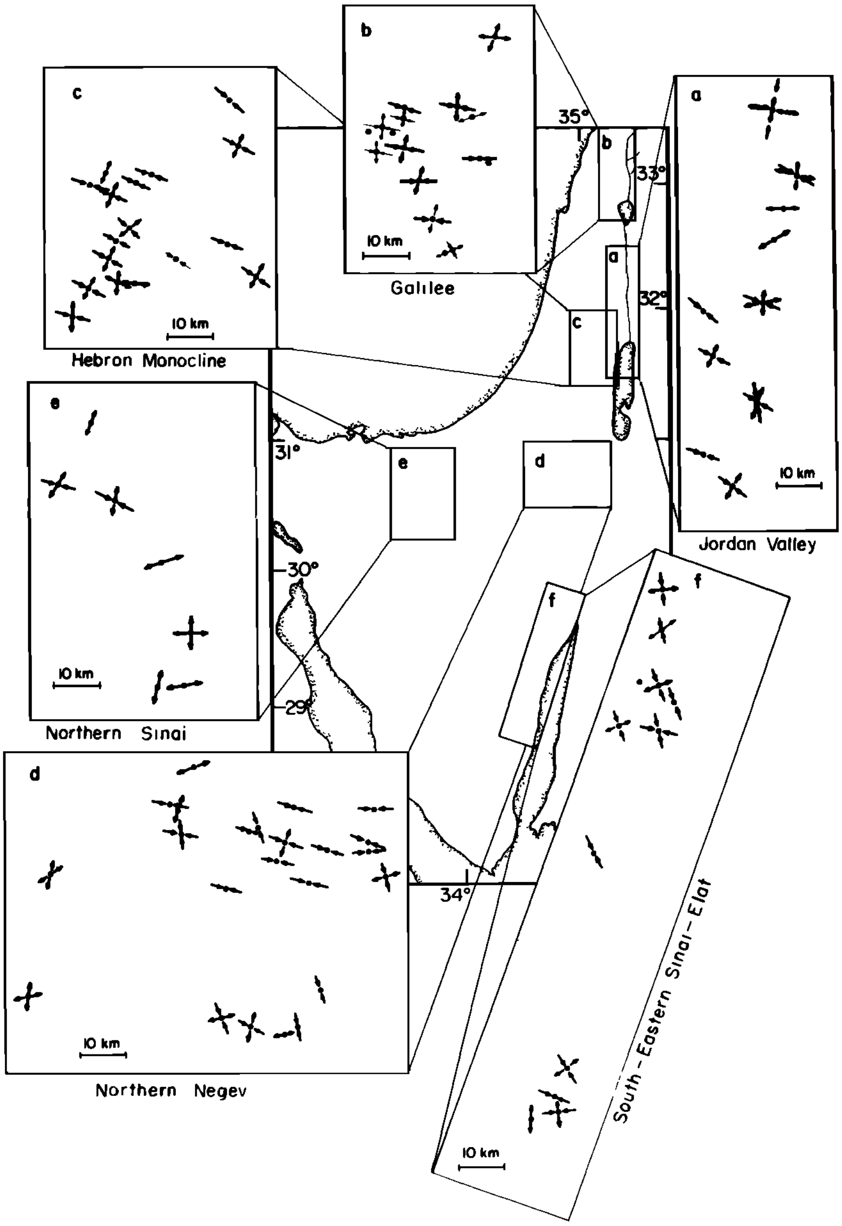

Fig. 10. The orientations of sub-horizontal principal strain axes measured in all stations in six subregions. A summary rose diagram for each subregion is shown in Figure 7.

are almost identical to the axes of the Dead Sea strain (Figure 7c). Therefore, we conclude that the Dead Sea strain is active presently at least along the rift itself.

DISCUSSION

Mesostructures may provide coherent strain patterns as demonstrated above. Indeed, mesostructures have been used in many tectonic investigations in the Levant and elsewhere; however, in the present study we will discuss solely the works with tectonic implications to the Sinai - Israel region.

The Syrian Arc Stress

The axes of the 'Syrian Arc strain,' deduced from mesostructures, have orientations that appear to be independent of the orientations of the host macrostructures (Figure 10). Eventhough the mesostructures are not homogeneously distributed, they are ubiquitous, they are found in all areas and in most rock types, and they indicate an outstanding homogeneity of the strain in all sub-regions. These observations indicate that the Syrian Arc strain formed under a uniform, regional tectonic stress. The magnitude of the strain associated with the mesostructures, seems to be small, on the order of a few percent [Reches, 1976]. Therefore, we regard the strain axes as a good estimates of the paleo-stress axes, which we call 'Syrian Arc stress.'

The trends of the folds and monoclines of the Syrian Arc vary systematically from almost N - S direction (e.g., the Hebron monocline) to almost E - W direction (e.g., folds in northern Sinai) forming an S shaped feature 1000 km long (Figure 1). The mesostructures that we measured formed during early stages of folding of the large folds and monoclines, and indeed, the mesostructures in many stations are consistent with the host structures (e.g., Figure 3). However, the orientations of the mesostructures in other stations may deviate from the orientation of the host large structure. For example, the maximum compressive axis associated with small faults in the Hazara monocline (z in Figure 1) is oriented up to 45° with respect to the axis of the monocline [Reches, 1976]. Or, the compression axis determined from tectonic stylolites in the Gebel Moghara anticline, northern Sinai (M in Figure 1), plunges 20°/296°, whereas the axis of this anticline trends generally toward WSW. Another example is the compression axis according to tectonic stylolites which parallels the strike of major normal faults in the western Galilee [Ron and Eyal, 1981].

Measurements of recent stress fields in the U.S.A. point the way to a possible explanation for the apparent difference in strain axis orientation for the meso- and macrostructures in the Sinai - Israel region. Zoback and Zoback [1980] presented the state of stress for the last five million years as determined by in situ stress experiments, focal plane solutions and geological structures. They found that the stress axes have relatively uniform orientations over large regions of 200 km to 2000 km long; these orientations are almost independent of old structures that are few tens of kilometers long or less [see also Sbar and Sykes, 1973].

We raise the hypothesis that the stress field that produced the mesostructures of the Syrian Arc in the Late Cretaceous is a paleo-analogue, in kind, of the recent stress field in the U.S.A. In that framework the mesostructures are viewed as accurate representations of the stress field whereas the macrostructures only crudely represent that same stress field.

This model is examplified here by a simple case (Figure 11): a horizontal tectonic compression is applied on a region which includes a preexisting fault of finite length. As the active tectonic stress may be unrelated to old structures, the fault in the model could be in arbitrary orientation with respect to the maximum compressive axis. One can recognize two stages of the deformation. During the early stage of the tectonic activity, the preexisting fault is still inactive, but local, minor yielding causes small scale faulting and vein opening as well as pressure solution and twinning (Figure 11a). The layers are sub-horizontal at this stage and therefore, the mesostructures indicate layer-parallel shortening. The uniform strain that is associated with the mesostructures developed during this stage.

During the second stage large slip occurs along the preexisting fault. This slip may lead to the development of a monocline or a fold (Figure 11b). The trend, dimensions, and character of the monocline or the fold are determined primarily by the fault; for example, the axis of the monocline will be parallel to the fault, but not necessarily normal to maximum tectonic compression [e.g., Reches, 1978]. Thus, the monocline (or fold) represents non-uniform strain accommodated by slip, fracturing, bending and buckling, in proximity to the fault. This accommodation of the tectonic strain during the second stage probably causes a regional decrease of the magnitude of the tectonic stresses. Such post-yielding decrease has been observed in faulting experiments [e.g., Brace, 1964] as well as folding experiments [e.g., Handin et al., 1972]. The activity of the mesostructures probably ceases due to this stress decrease.

Indeed, some field observations of Syrian Arc folds seem to support the above model. These observations indicate that eventhough folding initiated during Early Senonian, many folds and monoclines in Israel attained less than a half of their finite amplitude by Early Miocene [e.g., Gilat, 1977; Eran, 1982; Y. Bartov, perso-

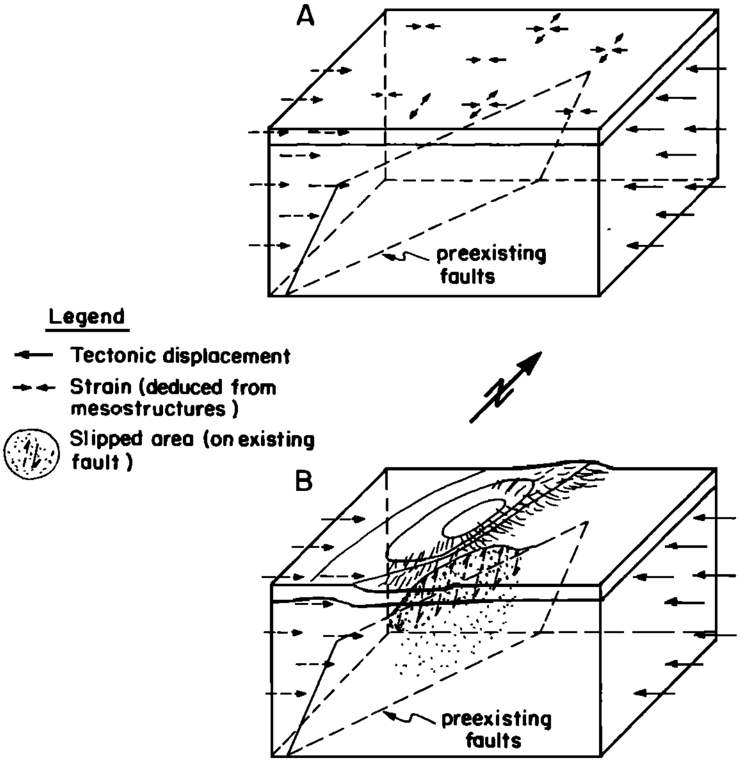

Fig. 11. A schematic model of sub-horizontal tectonic compression applied on a region which includes a preexisting fault (see text). (a) The uniform strain before the slip. (b) The nonuniform strain after the slip.

nal communication, 1982]. Therefore the second half of the folding occurred later, during the Miocene-Pliocene or even during the Pleistocene. The pre-Miocene period of Syrian Arc folding seems to correlate with the first stage of the model (Figure 11a): gently tilted layers of open folds with layer-parallel compression accommodated by mesostructures. The Miocene to Pleistocene period correlates with the second stage (Figure 11b): amplification of folds primarily by limb rotation rather than deformation by mesostructures.

The Dea Sea Stress

Mesostructures that indicate the Dead Sea stress lack uniform distribution (see above). They are found primarily in the Dead Sea rift with ENE to E extension; they also occur along the west margins of the rift, indicating compression directions of about NW-direction (Figure 3c) (which are intermediate between the Dead Sea strain and the Syrian Arc strain). Furthermore, few stations within the Israel - Sinai subplate exhibit the Dead Sea strain, with (Figures 5 and 10) or without (e.g., stations 7 and 10, Figures 4b and 4c, respectively, and Figure 10) the Syrian Arc strain.

This nonuniform distribution of the Dead Sea strain could reflect nonuniform distribution of the tectonic stresses or nonuniform mechanical properties of the crust. As the source of motion along the rift is of continental scale, we think that the second possibility is more reasonable. We envision large-scale motion of the Arabian plate with respect to the African plate, which has deformed the Sinai - Israeli subplate as well as the Dead Sea region. The elastic deformation of the two zones had similar orientations, however, the two zones behaved differently. The subplate behaved rigidly and thus underwent negligible permanent deformation, whereas the rift zone behaved as a weak region that deformed permanently. The concentration of permanent deformation along the Dead Sea rift has led to further weakening of this zone, which enhances the local deformation.

The existence of an ancient, weakened

zone along the Dead Sea rift may be manifested in the lower levels of the crust as well as in the crystalline basement and the sedimentary sequence. According to several investigators, sedimentary and structural features in rocks of Late Precambrian to Senonian indicate a pre-Miocene active zone along the present day rift [e.g., Bentor and Vroman, 1960; Bender, 1968; Bartov, 1974; Zilberfarb, 1978]. Garfunkel [1970] argued that some of that evidence is not conclusive. He further claimed that the Dead Sea rift is not parallel to the major Precambrian structures, at least in the Sinai region. Owing to limited exposures in critical regions, it is difficult to show directly the existence of a proto Dead Sea zone. However, our interpretation of the strain and slip concentration within the rift, supports indirectly the possibility of ancient weakness of this rift.

The Transition zone. The stress field on the western margin of the Dead Sea rift differ in orientation from both the Syrian Arc stress and the Dead Sea stress (station 6, Figures 3c and 10). It is possible that the stress in the transition zone reflects the rotation of marginal blocks. According to Freund [1974], anticlockwise rotation occurs in a wide zone of left-lateral shear, due to right-lateral slip along secondary faults. Indeed, H. Ron (personal communication, 1982) recognizes significant anticlockwise rotations at the margins of the Dead Sea rift south of the Sea of Galilee. He measured the paleomagnetic axes in Miocene and Pliocene rocks and calculated their rotation with respect to their expected poles. Applying the rotation model to our area implies that the mesostructures of the Syrian Arc stress would be rotated in an anticlockwise sense, and their compression axes should thus trend W to WSW. Some observations in the Negev support this implication. Reches [1976, Figure 6] shows that compression axes according to small faults, which trend W to WNW in the Hathira monocline (T in Figure 1) trend W to WSW in the Hazara monocline (Z in Figure 2), about 10-15 km eastward. This corresponds to a 10^o to 20^o anticlockwise rotation of Syrian Arc mesostructures as the Dead Sea rift is approached. This rotation may also be reflected in the northward trend of the Hathira monocline close to the Dead Sea rift.

The mesostructures in central Israel behave differently. First, the Syrian Arc strain axes, within the Jordan Valley (a in Figure 10), are not rotated (stations 2, 4, and 8 in Figures 5, 7, 8b and 10). Second, the mesostructures on the western side of central Israel display W to WNW compression (Figures 6, 7, 8c and 10 and Reches et al. [1981]), whereas on the eastern side they show NW compression (e.g., station 6, Figure 3c). According to the rotation model the latter is viewed as a rotated Dead Sea axis, implying absence of Syrian Arc mesostructures in the eastern side of central Israel. We think that such absence is unlikely in view of the wide distribution of Syrian Arc mesostructures. Our interpretation is that the mesostructures in the eastern side reflect a tectonic stress field which is intermediate, both in orientation and location, between the two dominant stress fields. The development of such an intermediate field raises the possibility of simultaneous activity of the Syrian Arc stress and the Dead Sea Stress. This stage occurred after the time in which the Syrian Arc stress prevailed on both sides of the Dea Sea rift.

The Mesostructures and the Tectonic History of the Sinai - Israel Subplate Since the Cretaceous

A summary of the tectonic history of the Sinai - Israel subplate since the Late Cretaceous is presented here. It is based on the current study of mesostructures and previous regional investigations (Figures 12 and 13). We will discuss the development of three groups of macrostructures which dominate the structural fabric of the region: the Dead Sea rift, the E - W shear zone of Sinai - Negev and the Syrian Arc folds (Figure 1).

Pre-Cretaceous. Pre-Cretaceous tectonic activity is usually attributed to epirogenic movements of the Arabian massif., The interpretation of well logs and limited exposures of Lower Paleozoic rocks in southern Israel indicate general northwestward tilting of the margins of the massif with the development of a few wide basins [Weissbrod, 1981]. The Lower Paleozoic rocks are mostly clastic and platform carbonates. Upper Paleozoic rocks are essentially absent, excluding limited carboniferous rocks in western Sinai [e.g., Weissbrod, 1981]. Large, open and relatively deep basins developed during the Triassic and Jurassic period [e.g., Druckman, 1974; Goldberg and Friedman,

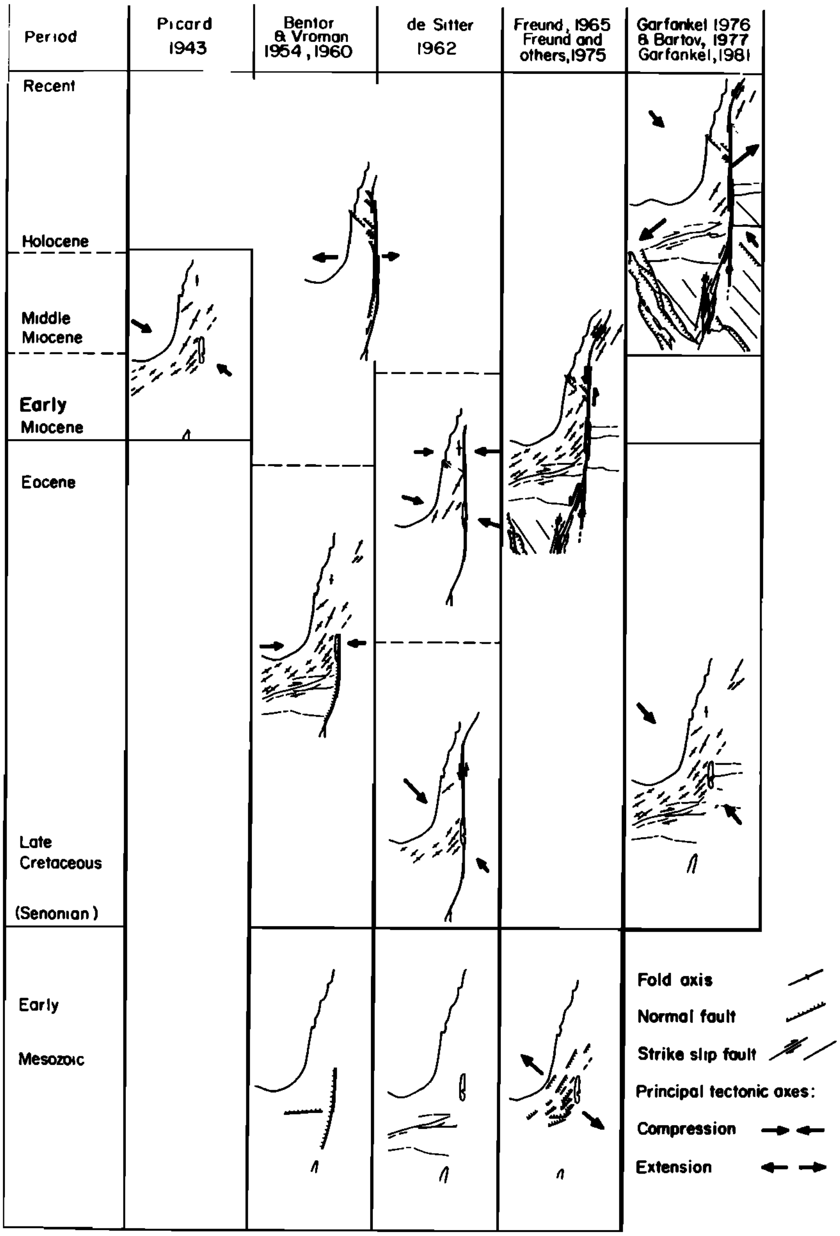

Fig. 12. The tectonic history of Israel - Sinai according to macrostructures as proposed by several investigators.

1974]. These basins seem to coincide, in part, with major anticlines and monoclines of the Syrian Arc system. This observation led Freund et al. [1975] to propose that the structural pattern of the Syrian Arc system had been established during Triassic and Jurassic (Figure 12). During those period the basins subsided along normal faults that formed due to regional extension in an E to ESE direction. The extension inverted to compression in the same orientation during the Late Cretaceous, causing reverse faulting along the old normal faults.

Cretaceous to Eocene. The Cretaceous to Eocene tectonic activity initiated with a phase of intense regional uplift and erosion associated with volcanism. It caused truncation as deep as the Paleozoic sequence in southern Israel. After several

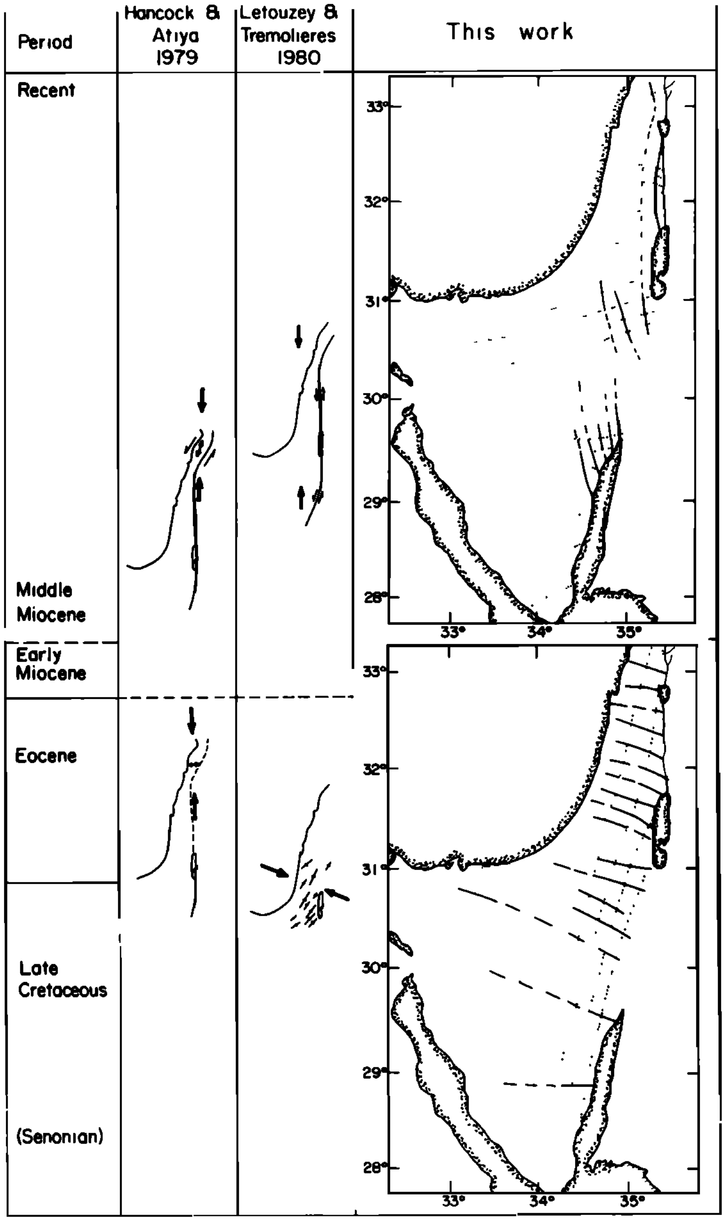

Fig. 13. The paleo-stress fields in the Sinai - Israel subplate based on mesostructures. The present work includes data from 130 stations distributed along the Dead Sea rift and within the subplate. Continuous heavy and dotted lines are the trajectories of the maximum and the minimum horizontal compressive axes, respectively; discontinuous lines are the same where inferred. The trajectories were drawn by extrapolation between individual stations (Figure 8). The spacing of the trajectories represents the abundance of evidence of the stress fields. The study of Hancock and Atyia (1979) represents data from Lebanon; the study of Letouzey and Tremolieres (1980) represents 17 stations in Israel.

phases of epirogenic movements during the Early Cretaceous, the folding and faulting of the Syrian Arc system started in the Senonian [Bentor and Vroman, 1960; Bartov, 1974]. Bentor and Vroman [1960] attribute the folding of the Negev anticlines to an E - W compression of the northern Negev against large blocks on the east and south (Figure 12). According to de Sitter [1962] a NW - SE compression prevailed up to the Middle Eocene, manifested by the folds of central and southern Israel. He further suggests that the N - S trending folds of the Syrian Arc in northern and central Israel, formed under E - W compression of post-Eocene pre-Quaternary age (Figure 12). Freund [1965] claimed that most of the structures in the Levant are secondary to the left-lateral shear along the Dead Sea rift, which started in the Late Mesozoic (Figure 10). Freund et al. [1975] suggest an inversion of the stress directions in the Levant during the Early Cretaceous (see above), which caused reverse faulting and folding along the Triassic - Jurassic normal faults. Bartov [1974] shows that faults of the E - W shear zone of Sinai, cut some of the Syrian Arc anticlines and therefore, these folds predated the strike slip motion along the shear zone. Bartov claims that the E - W shear zone has been sinistrally displaced, about 105 km, along the Dea Sea rift. Therefore, according to him, the Syrian Arc folding of the Israel - Sinai subplate predated the E - W shear zone of northern Sinai, which in turn predated the N - S faulting of the Dead Sea rift.

Mesostructures of the Syrian Arc strain. The mesostructures of the Syrian Arc strain presented here, are associated with the folding of the Syrian Arc system discussed above (Figure 13). These mesostructures indicate the following features of the Late Cretaceous to Eocene tectonic stress:

1. The stress orientations were uniform over the major part of the Sinai - Israel subplate (Figures 6, 7, 8, 9 and 10). The Dead Sea rift and the Sinai - Negev shear zone have no apparent influence on the orientation and the abundance of the mesostructures. The W to WNW horizontal maximum compression of the Syrian Arc stress is incompatible with both the left-lateral shear and the horizontal extension associated with the large structures of the Dead Sea rift. Therefore, the mesostructures analysis indicates that Syrian Arc folding predated the shear of the Dead Sea rift. On the other hand, as the Syrian Arc stress is compatible with the right-lateral slip of the Sinai - Negev shear zone (see below), they cannot be separated according to strain orientations alone.

2. In several locations the orientations of the paleo-compression axes are not perpendicular to the trends of the host monoclines and folds. Such deviations indicate that the trends of the large monoclines and folds were determined by preexisting macrostructures. The monoclinal nature of the Syrian Arc folds suggests that the preexisting structures are faults [e.g., Reches and Johnson, 1978]. The model of Triassic - Jurassic normal faulting of Freund et al. [1975] (Figure 12), is a likely explanation for these preexisting faults.

Post-Eocene. The Post-Eocene tectonism of the Sinai - Israel subplate involved amplification of the Syrian Arc folds as late as the Pliocene. However, the predominant activities were the breaking up of the subplate from the Arabian plate and the 105 km of left-lateral shear along the Dead Sea rift.

In the Sinai, the development of the Dead Sea rift was predated by the intrusion of large dikes during the Early Miocene. Recently, Eyal et al. [1981] have shown that Precambrian rocks in eastern Sinai are left-laterally displaced, by the same amount as the Early Miocene dikes, along N to NNE sinistral faults. This observation implies that no strike slip displacement occurred along the marginal faults of the rift before the Miocene.

The Sinai - Negev shear zone, which also displaces these Early Miocene dikes is displaced laterally about 105 km along the Dead Sea rift [e.g., Quennell, 1959]. Therefore, the Dead Sea rift postdates the Early Miocene [Bartov, 1974]. Some investigators suggest that according to local sedimentary and geomorphic evidence and magnetic anomalies in the Gulf of Aden, the main phase of shear along the rift initiated during the Middle Miocene [e.g., Garfunkel, 1981]. Others have proposed that the Dead Sea rift is not older than the Pliocene or even the Pleistocene [e.g., Picard, 1943].

Mesostructures. The mesostructures of the Syrian Arc stress were found in rocks as young as Middle Eocene. Mesostructures in rocks of Miocene age or younger are of Dead Sea stress. However, a few lines of evidence suggest that the Syrian Arc deformation prevailed in the subplate during the Miocene and possibly the Pliocene. First, the right-lateral slip that occurred along the E - W shear zone after the Early Miocene [Bartov, 1974], fits well the WNW compression of the Syrian Arc stress, and does not fit the N to NNW compression of the Dead Sea stress. Second, the transition zone with NW compression axis along the eastern side of central Israel (Figure 3) probably formed under simultaneous activity of both dominant stress fields (Middle Miocene? Pliocene?). Third, Schulmann [1981] mentioned that dikes of Miocene and Pliocene age in northern Israel trend toward the WNW and NNE, indicating NNE extension (the Syrian Arc strain) and WNW extension (no corresponding mesostructures). Finally, folding of Miocene and Pliocene layers with Syrian Arc structures in Israel [Gilat, 1977] and close to or within the rift [e.g., Eran, 1982]. These observations raise the interesting possibility of simultaneous activity of the Syrian Arc stress and the Dead Sea stress. The existence of a weak zone along the Dead Sea rift may cause simultaneous deformation with different orientations.

Both strain systems described here reflect the internal deformation of the continental subplate of Sinai - Israel, located within the region of collision between Africa, Arabia and Euroasia plates. The Syrian Arc and Dead Sea stresses are currently applied by us as essential elements for modelling the adjacent plates motion.

Acknowledgments. We thank R. Shagam, M. Eyal, M. Sbar, M.L. Zoback, N. Mittlefeld for many stimulating discussions, H. Ron, who kindly permitted us to use part of his unpublished data, and J. Fink, D. Hoexter, and H. Ron, who joined us in the field. The paper was reviewed by R. Shagam and Y. Bartov. The assistance of Y. Barbut and S. Fliegelmann is greatly appreciated. The study was supported by grants from the Israel Commission for Basic Research and U.S. - Israel Binational Science Foundation grant 1820.

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(Received November 1, 1982;
revised January 20, 1983;
accepted January 25, 1983.)