THE STRUCTURE OF A MONOCLINE IN THE SYRIAN ARC SYSTEM, MIDDLE EAST–SURFACE AND SUBSURFACE ANALYSIS

Ze'ev Reches*, David F. Hoexter* and Francis Hirsch**

The long Syrian Arc belt in the Middle East consists of tens of folds and monoclines with their associated faults. The structure of one monocline of this belt, the Hebron monocline in Israel, is analyzed by construction of accurate structural traverses, measurement of the internal strain of the rocks, and geological mapping. The surface structure indicates that three modes of monocline development, draping, buckling and kinking, operated in the Hebron monocline. The subsurface structure, which includes a steep reverse fault, is deduced through mechanical and tectonic models, and structural similarity with other monoclines in Israel.

INTRODUCTION

The analysis of the exposed structure of the monocline of Hebron, Israel, and an interpretation of its subsurface structure are presented in this study.

Monoclines usually develop in sedimentary sequences of intermediate thickness, commonly with involvement of the crystalline basement (Harding and Lowell, 1979). Typically, monoclines contain one main fault zone, with throw comparable to the uplift of the monocline, and many small faults; faults with intermediate throw are relatively rare. Large detachment surfaces have been suggested to explain the gross shape of a few monoclines, and therefore, to determine the subsurface structure of a monocline, one has to evaluate the throw, attitude and the location of the major fault of the monocline, and the level and amount of possible detachment. The quality of the proposed subsurface geometry depends on the accuracy of the surface mapping as well as a good understanding of the mechanism of monocline development.

The Hebron monocline is one of tens of folds and monoclines comprising the Syrian Arc system (Fig. 1). This belt of folds, about 1,000 km long, is developed on the margins of the Arabian Shield, within a sequence of sedimentary rocks of platform type. The system consists mostly of open flexures and folds, frequently associated with reverse and wrench faults (e.g. Krenkel, 1929; Hensen, 1951; Freund, 1965). The tectonic deformation of this belt was initiated by differential subsidence in Triassic-Jurassic times, but the main phase that shaped its present structure is the tectonic compression of Senonian to at least Neogene time. The breaking up of the Levant along the Dead Sea rift, during the Neogene, slightly modified the already-developed folds. Only a few, small, oilfields have been found in the Syrian Arc system, in spite of the promising combination of simple closed structures with

*Department of Applied Mathematics, The Weizmann Institute of Science, Rehovot, Israel.
**Geological Survey of Israel, Jerusalem, Israel.

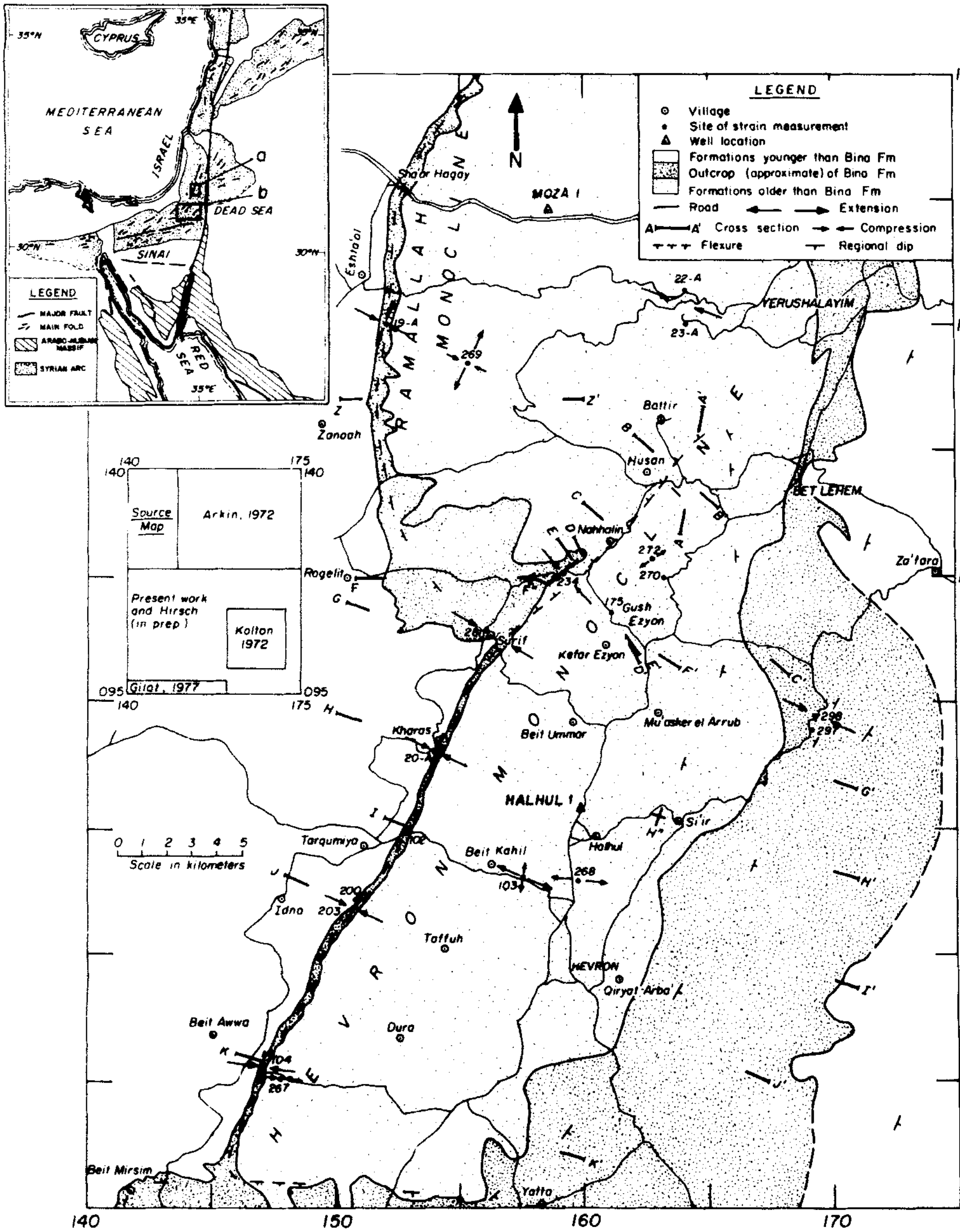

Fig. 1. Location map of the study area. The regional tectonic map is shown in upper left: a—study area; b—northern Negev. Included in the main map: locations of structural traverses, A-K and Z; location of stations of small-scale structures with the derived strain axes and generalized geology. Grid numbers refer to Israel Grid of co-ordinates.

thick shallow marine and continental sedimentary rocks.

In the first part of this paper, the gross structure of the Hebron monocline is described, together with the internal strain of its rocks. Based on these data, the mechanism which formed the monocline is derived, followed by a discussion of the subsurface geology based both on the mechanism of the development of monoclines and on structural similarity with monoclines in Israel and elsewhere. Finally, implications for structural traps in the Hebron monocline are briefly discussed.

THE HEBRON MONOCLINE

The two NNE-trending large monoclines of

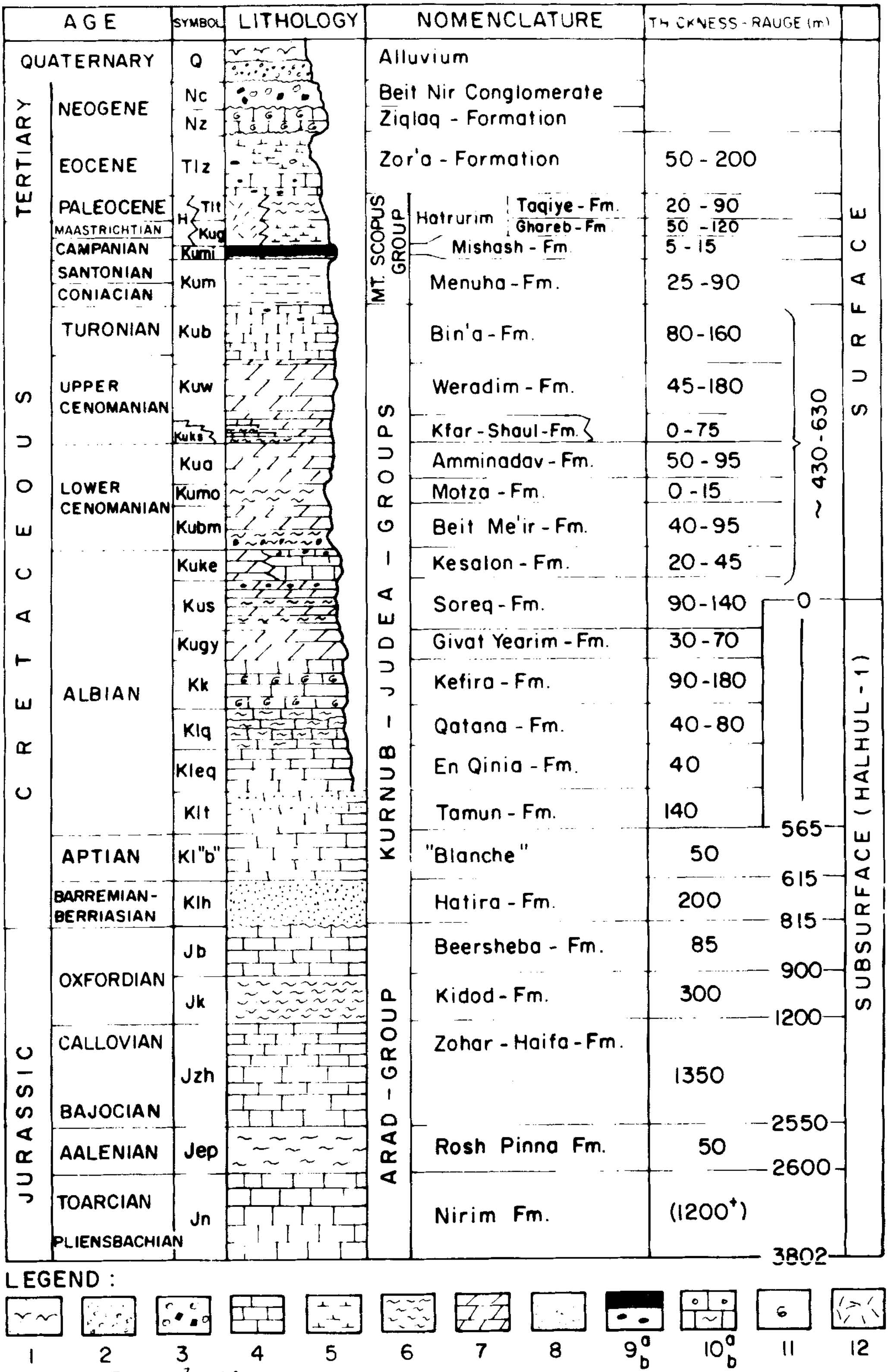

Fig. 2. Generalized stratigraphic section of the Hebron monocline. Legend: 1 alluvium, soils; 2 fluviatile gravels; 3 polymict conglomerate; 4 limestone; 5 chalk; 6 marl; 7 dolomite; 8 sandstone; 9a chert, massive; 9b chert, concretion; 10a oolite; 10b limestone and marl; 11 fauna abundant; 12 metamorphic; 13 unconformity; 14 lateral change.

Hebron and Ramallah form a prominent backbone between the Mediterranean Sea and the Dead Sea Rift valley (Fig. 1). The cities of Jerusalem, Bethlehem and Hebron are located close to the crestal zone of the Hebron monocline.

The study area is approximately 25 × 40 km in size; the work included mapping the surficial geology of much of this area, at a scale of 1:50,000 (Hirsch, *in prep.*), and conducting detailed surface traverses at intervals of between three and six km. By mapping tectonic stylolites, extension veins, small-scale faults and similar features, the internal strain in the monocline was determined and finally, the subsurface structure was constructed, using a modified Busking method at a scale of 1:20,000. Detailed cross-sections were then fashioned.

Previous work in the Hebron area includes studies by Rofe and Rafferty (1963), Cook (1971), Kolton (1972), and Arkin (1976); Gilat (1977) recently mapped the southern part of the Hebron structure. A large segment of the region is currently being mapped by Hirsch as part of the 1:50,000 geological map of Israel. One wildcat borehole, the Halhul-1, was drilled to a depth of 3,860 m in 1966, and was found dry.

Stratigraphy

The stratigraphy exposed in the studied area is dominated by limestone, dolomite and chalk of Albian (Early Cretaceous) to Middle Eocene age. Neogene limestones and conglomerates cover plateaux between 400 and 550 m above m.s.l., cutting Cretaceous to Eocene strata. Earlier Cretaceous (Kurnub Group) and Jurassic (Arad Group) strata have been penetrated by deep drillings (Fig. 2). The limestones and dolomites which are exposed on the upper region of the Hebron monocline compose part of the intake area for the Cretaceous aquifers of Israel.

Subsurface stratigraphy. Several deep wells have reached the Arad Group of Jurassic strata in the Ramallah, Jerusalem and Hebron areas. Some 4,000 m composed mainly of carbonates of Oxfordian to Liassic age were found in Ramallah-1 16 km north of Jerusalem. In Halhul-1 (Fig. 1) almost 3,000 m were penetrated, and a thickness close to that found in Ramallah-1 might have been expected. The top of the Jurassic sequence is truncated by the regional Early Cretaceous unconformity. The thickness of the Kurnub Group of Early Cretaceous age reaches some 350 m in Halhul-1.

The surface stratigraphy of the Hebron monocline includes the Judea Group of Albian-Cenomanian-Turonian age, and the Mount Scopus Group of Senonian-Paleocene age. The predominant carbonate sequence of the Judea Group can be divided according to its exposures and lithology into three main subdivisions: mainly limey to shaley lower part (Kleq, Klq, Kl) of Albian age in the deep gorges cutting the central domes of the Hebron and Ramallah uplifts; dolomitic, shaley and minor limey middle part (Kugy, Kus, Kuke, Kubm, Kumo) that builds the terrace landscape of the higher zones of the Hebron and Ramallah uplifts (Albian-Cenomanian); upper part of

Section	*Shortening along Moza Formation*			*Structural uplift*		*Through elevation of Base Moza Fm. above m.s.l. (m)*
	of flexure (%)	*Overall (m)*	*Overall (%)*	*of flexure (m)*	*Overall (m)*	
A	~0	10	0.2	160	220	—
B	~0	10	0.3	200	260	660
C	4.5	100	1.0	370	370	610
D	3.6	90	1.6	620	620	445
E	3.1	90	1.6	560	560	520
F	6.8	310	1.5	1040	1040	20
G	9.0	330	1.5	1000	1000	5
H	9.3	400	2.1	1160	1160	−100
I	10.0	280	1.4	850	1220	−80
J	11.5	300	1.5	880	1170	−160
K	5.8	160	1.1	680	800	40

Table 1. Structural data of the 11 sections across the Hebron monocline; locations of sections are shown in Fig. 1. The shortening is the difference between the length along the deformed Moza Formation and the horizontal distance that it occupies. Section A parallels the axis of monocline.

mainly dolomites and lithographic limestones on top of the steep flank of the monoclines and lower zones of the Ramallah and Hebron uplifts (Cenomanian-Turonian) (Kua, Kuks, Kuw, Kub).

Structure

The gross shape. The Hebron structure is a doubly-plunging NNE-SSW trending monocline, about 35 km long, with some branches to the south (Figs. 1, 3). The steep monoclinal flexure, which dips up to 50°, separates a down-thrown western block and an uplifted eastern block. The topographic units correlate in general with these structural divisions and the details of the gross structure are revealed by construction of ten accurate cross sections, presented in Figs. 1 and 3, and Table 1. The construction method is a modified Busking technique, and is described in the Appendix.

The gross shape of the Hebron monocline is presented in a block-diagram of the structure at the Moza Formation (Kumo) level, based on eight traverses (Fig. 3). Structural contours and the crestal line of the base of the Moza Formation were drawn between the individual traverses (Fig. 3). Structural details between the traverses are inferred.

The Hebron monocline has a relatively flat, undulatory crest line (Fig. 3). Highest structural elevation of the base of the Moza Formation is 1,140 m in section I, and it plunges gently, about 1.2°, to the north and south. The structural plunge steepens to about 3° at the northern and southern ends (Sections A, B and J, K respectively). The structural uplift increases continuously from the north (Section B), towards the south (Section I), with an abrupt increase between Sections D-E and F (Table 1). This increase is due to a marked decline in the elevation of the trough of the synclinal bend (Table 1), rather than an increase in the elevation of the crest, and the increase of uplift correlates to the increase of the thickness of the sequence between the Moza (Kumo) and Bina (Kub) Formations (Hirsch, *in prep.*). These changes occur within the overlap zone between the Hebron and Ramallah monoclines.

The ten profiles of the monocline show both a synclinal bend and an anticlinal bend; at the Moza Formation level, the former is usually the tighter of the two. Open, domal anticlines are associated with the anticlinal bend in several section (Fig. 4, Sections B, C, D, E, F and G), while the other sections have a straight tilted segment above the anticlinal bend (Sections I, J and K).

The profiles of the Hebron monocline display both continuous flexures (Sections B and K; Fig. 4), and kinked flexures (Sections C, D, E, F, G, H, I and J). The former type is characterized by a smooth transition between concentric sections, whereas the latter type

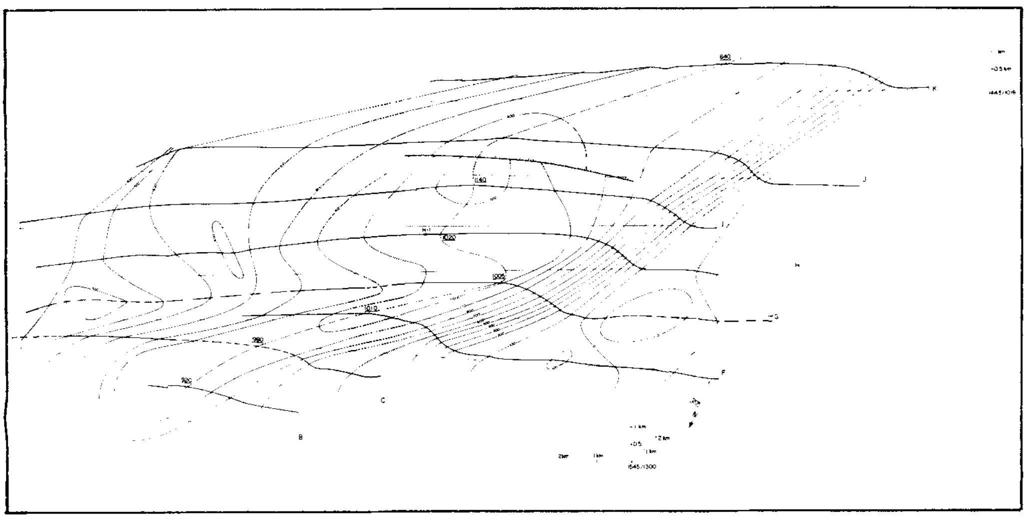

Fig. 3. The surface structure of the Hebron monocline at the base of the Moza Formation. Eight accurate cross sections were located in their relative positions, displaying the gross shape of the monocline (Fig. 1). Structural contours and the crestal line are traced on the block diagrams. Contours between sections are inferred. Every section has a base line which is horizontal at sea level. All elevations are in m above m.s.l.

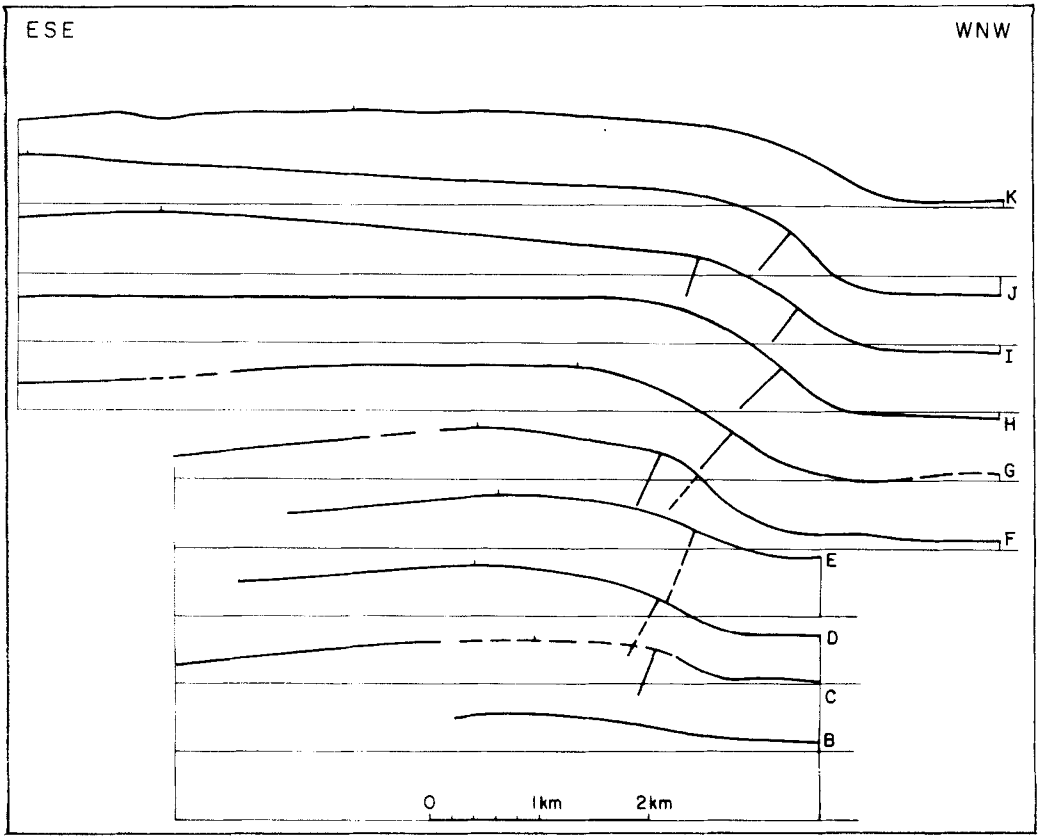

Fig. 4. The profile of the Hebron monocline shown in ten accurate sections of the base of Moza Formation. The presented profiles are segments of the complete sections (Figs. 1, 3). The inclined lines in the flexure zone show the binge zone, of "mis-match" of concentric arcs.

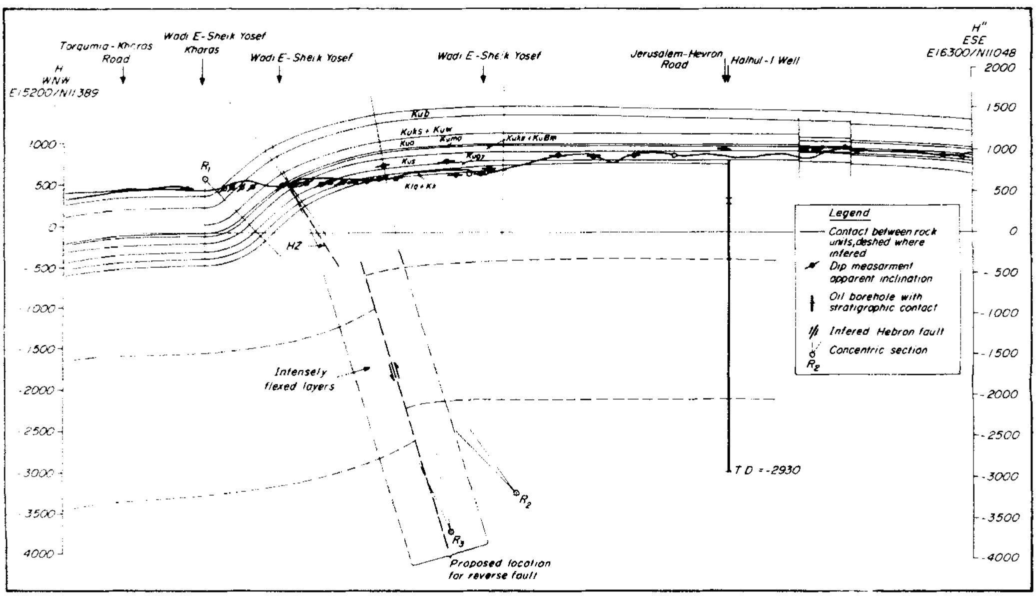

Fig. 5. The measured surface and interpretative subsurface structure of the Hebron monocline along Section H (location in Fig. 1). Stratigraphy after Fig. 2. Elevation in meters. Vertical and horizontal scales are equal.

contains zones of "mismatch". For example, in Section H (Fig. 5) the section with center R_2 does not continue smoothly to the section with center R_3 (see Appendix); the zone between the two concentric sections, H_Z in Fig. 5, is a zone of fast change of dip, and high curvature, and is a possible locus for rock brecciation and minor faulting (e.g. Stearns, 1971). The hinge zones of the kinked flexures are marked also on the other profiles (Fig. 4).

The shortening and structural uplift of the monoclinal flexure, as well as the overall structure, were measured along the profiles (Table 1). The shortening is the difference between the length along the flexed Moza Formation and the horizontal distance it occupies; the structural uplift is the difference in the altitudes between trough and crest of the base of the Moza Formation. The results of these measurements (Table 1), indicate that the maximum overall shortening of the overall structure is 400 m, or 2.1%, in Section H. The maximum shortening of the monoclinal flexure is 11.5% in Section J, where maximum dip is 50°.

Small-scale structures. The mechanisms which govern the development of monoclines can be revealed by knowing both the gross shape of the structure, as described above, and its internal deformation, which will now be discussed (Reches and Johnson, 1978). The internal deformation of the Hebron monocline has been evaluated by measuring small-scale structures with apparent displacement; mostly tectonic stylolites, small faults, filled veins and slickolites were measured, all indicating the sense and the nature of the internal deformation (Fig. 6). Many road cuts, quarries and natural cliffs were surveyed in search of stations with ample data, although in many sites no mesoscopic structures were found. Eighteen stations in the Ramallah and Hebron monoclines (Fig. 1) were located, and at each station several tens of individual structures, commonly of several types (Table 2) were measured; the pattern of the small structures was remarkably consistent at each site and was furthermore consistent for most stations in the study area (after retilting bedding to the horizontal) (Figs. 1, 7; Table 2).

The predominant strain pattern in the Hebron monocline consists of a horizontal compression axis with mean trend of N64°W-S64°E (Fig. 7; Table 2); this axis is associated in several stations with a horizontal extension with mean trend of N26°E-S26°W. This strain

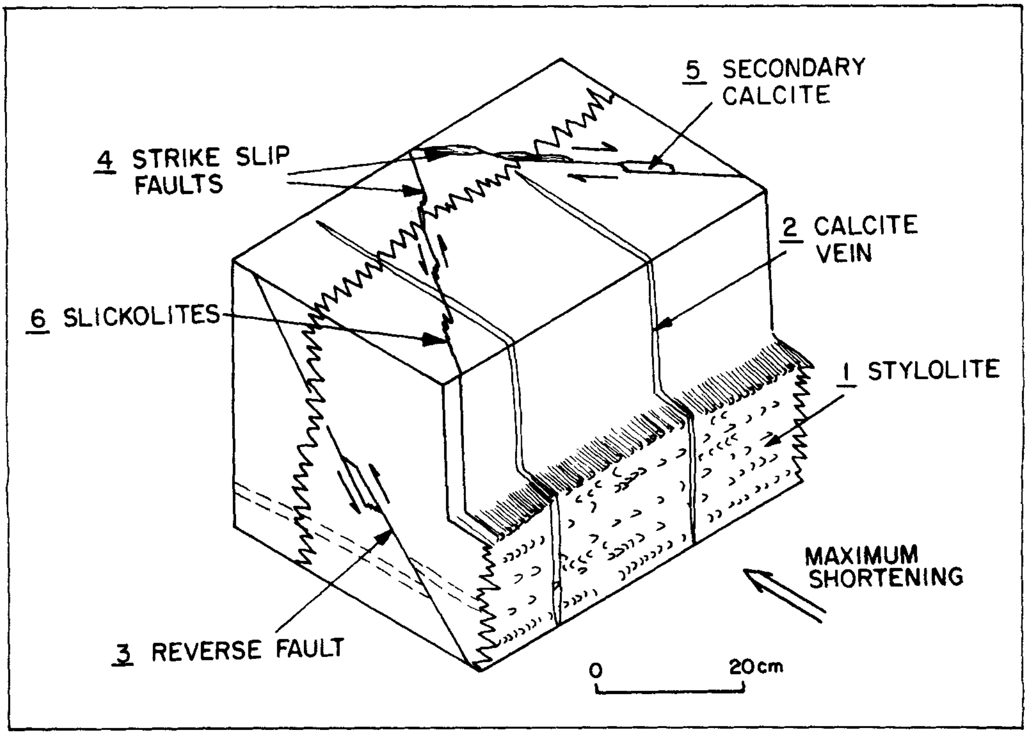

Fig. 6. Schematic presentation of the small-scale structures measured in this study.

Station	Rock unit	Local dip	Structural position	Type of small structures	Number of data points	Quality	Primary strain axes	Secondary strain axes
19-A	Kub	26°	FL	S	30	E	CO-293°	—
20-A	Kub	45°	FL	S, F, V	47	E	CO-297°	EX-025°
22-23-A	Kus	~0°	U	S, F	52	E	CO-290°	—
102	Kub	38°	FL	V, S, F	41	E	EX-020°	CO-20°/130°
103	Kugy	6°	U	V	52	G	EX-293°	EX-008°
104	Kub	28°	FL	S, V	62	E	CO-287°	EX-286°
—	—	—	—	—	—	—	EX-003°	—
175	Kus	4°	FL-U	V	22	P	inconclusive	
200	Kum	35°	FL	F	12	P	—	EX-026°
203	Kub	47°	FL	F	13	G	CO-296°	—
234	Kub	~0°	D	F, V	57	G	CO-314°	EX-052°
267	Kua	16°	FL	F	10	G	CO-278°	—
268	Kus	5°	U-FL	F	15	G	EX-276°	—
269	Kubm	6°	U-FL	F	30	G	EX-024°	CO-292°
270	Kubm	6°	U	F	13	P	—	EX-056°
281	Kub	7°	FL-D	S	7	G	CO-296°	—
297/8	Kub	10°	U	F, S	40	E	CO-303°	—

Table 2. Summary of the stations of small-scale structures; locations of stations are shown in Fig. 1. Rock units after Fig. 2. FL—located in the monoclinal flexure; U—located in the uplifted block; D—located in the downthrown block. Type of small structures measured in a given station: S—tectonic stylolites; F—small faults; V—extension vein. Quality of results: E—excellent; G—good; P—poor. Strain axes are sub-horizontal unless otherwise marked. CO—compressive strain; EX—extensive strain. Stations 19-A, 20-A, 22-A and 23-A from Eyal and Reches (*in prep.*).

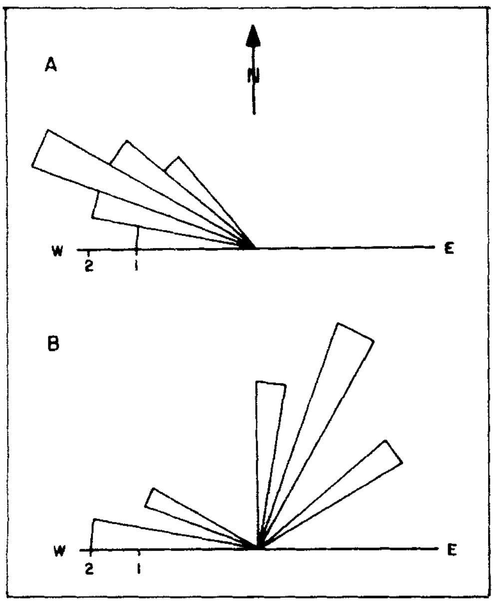

Fig. 7. The orientation of the horizontal strain axes measured in 18 stations in the Hebron monocline (Table 2). All data after retilt of bedding to horizontal. Primary and secondary strain axes (Table 2) have the same weight. A—compression axes; B—extension axes.

field has a simple relationship to the trend of the Hebron monocline: its compressive axis is subperpendicular to the trend of the flexure, and the extension axis is subparallel to it. Furthermore, this strain field is consistent with the regional strain field that prevailed in Israel from the Senonian to the Eocene, as determined through a regional study of small structures (Reches and Eyal, 1979).

In two stations predominant extensions, with mean trends of N75°W-S75°E were found subparallel to the dominant compression noted above. These two stations were located in the crestal region of Section I, which has the largest overall uplift (Fig. 4; Table 1). The significance of these two stations is discussed in the next section.

Mechanism of development of the Hebron monocline

Monoclines can be generated through three main modes: buckling, draping and kinking (Reches and Johnson, 1978). In the *first mode* (buckling), the sedimentary sequence is subjected to layer-parallel shortening, and it buckles into the asymmetric monocline due to an initial dip or an underlying fault. In the *second mode,* the sedimentary sequence is draped by differential vertical displacement above a fault or an igneous intrusion. The *third mode* (kinking), is dominant in sedimentary sequences with high frictional resistance between the layers and here, as with the buckling mode, layer-parallel shortening is essential. The dominant modes in the generation of a given monocline can be determined by using the criteria suggested by Reches and Johnson (1978, p. 301), summarised below.

Drape Folding

1 monoclinal flexure is simple, with open anticlinal and synclinal bends;
2 curvature increases downwards;
3 vertical displacement is constant or decreases upwards;
4 there are zones of layer-parallel extension and zones of layer-parallel shortening.

Buckling

1 monoclinal flexure is associated with an anticline and a syncline;
2 curvature is constant, increasing or decreasing upwards;
3 vertical displacement is constant, or increases upwards;
4 layer-parallel shortening prevails at all levels.

Kinking

1 straight limbs and distinct hinge zones are present;
2 internal strain indicates layer-parallel shortening at all levels;
3 there is yielding or faulting in tight hinge zones.

The application of these criteria to the Hebron monocline indicates that all three models were involved in its development. For example, the Hebron monocline has an open simple flexure in Section K, in agreement with Criterion 1 for draping. Also, other Sections (B, C, D, E, F and H), have anticlinal domes, as with Criterion 1 for buckling, while straight segments, typical of kinking, dominate Sections I, J and K. Another criterion is the internal strain distribution. The evidence for prevailing layer-parallel shortening in the Hebron monocline is characteristic for the buckling and kining modes (criteria 4 and 2 respectively); however, the layer-parallel extension found in the anticlinal bend of Section I is typical of the draping mode (Criterion 4).

Thus, criteria of all three modes (draping, buckling and kinking) were found to occur in the Hebron monocline. An appealing model that fits all these features is that the Hebron monocline overlays a steep reverse fault, which was activated by horizontal tectonic compression. The displacement along the reverse fault during the early stages of deformation provided both the subhorizontal compression observed in the rocks, and the localization mechanism for the monoclinal flexure. In later stages, when extension dominates (Freund, 1979), small normal faults developed in the anticlinal bend of the area with the largest uplift.

DISCUSSION

The study of the surface structure of the Hebron monocline reveals an elongated structure, with a smooth or kinked monoclinal flexure, which is most probably underlain by a reverse fault—the Hebron fault. The determination of the inclination, throw and location of the fault which underlies the monocline, is difficult (e.g. Reches, 1978). Here, however, an attempt at deducing the subsurface structure of the Hebron monocline is made by comparison with similar monoclines in southern Israel together with theoretical models.

Several reverse faults which are not exposed at the surface have been penetrated by wells in Israel's Negev region, south of the Hebron area (Fig. 1). These reverse faults were detected in five boreholes penetrating four monoclines (e.g. Coates *et al.*, 1963; Mimran, 1976; Aharoni, 1976). These faults have considerable throw, from one third to the complete uplift of the host monoclines at depths of up to 2.5 km (Table 3). They are steeper than 45° and usually fall within the 60°-80° range. In two boreholes normal faults were found close to the reverse ones.

These reverse faults could be generated by several mechanisms, of which one is reverse faulting in the core of a concentric flexure, during the development of the monocline. Such faulting occurs through the yielding of rocks in the loci of high curvature; in this case, the fault initiates at the center of a concentric section of a fold (points R_2, R_3 in Fig. 5), and its displacement increases downward. However, as the center of concentricity of the monoclinal flexures of the northern Negev is 1.5-4.0 km deep, and the fully-developed reverse faults are found at shallower depths, one must reject this mechanism for this area.

Another mechanism of fault generation suggests that the fault preceeded the monocline, and that it was reactivated by the tectonic stresses which generated the monocline, the fault thereby determining the location, shape and strain of *the monocline*. The pre-existing fault may occur within a crystalline basement (e.g. Stearns, 1971), or within a sedimentary pseudo-basement (e.g.

Name of monocline	Maximum uplift of monocline (m)	Penetrated depth to fault (m)	Vertical separation of fault (m)
Zohar	510	1096	148
Barbur	420	2427	180 +
Rechme	440	2275	275 +
Sherif	180	2396	231

Table 3. Borehole data on the reverse faults in monoclines of the northern Negev. The (+) sign indicates minimum separation (after Aharoni, 1976).

Reches, 1978). Both true and pseudo-basements apply *displacement* on the base of the overlying sequence, and thus are equivalent from a mechanical point of view.

It has been observed in simple monoclines that the major fault propagates only a short distance into the overlying sediments. For example, in the Palisades monocline, Colorado Plateau, the major fault propagated about 60 m into the sediments above it, even though the total throw along the fault at depth is about 250 m (Reches, 1978). In the Palisades monocline, the pre-existing fault in the Precambrian rocks is replaced by a tight, continuous flexure in the Lower Paleozoic rocks. This short distance of propagation is due to the tendency of the layered sedimentary rocks to fold, rather than to fault, above a steep reverse fault.

It seems that the pre-existing fault concept fits the reverse faults of the northern Negev. However, it is not clear if these faults propagated from a crystalline basement, or if they existed within the sedimentary sequence (see also Mimran, 1976). If the faults existed in the crystalline basement, at depths of 4-5 km, they should have propagated 2.5-4.0 km in order to be detected in the oil boreholes (Table 3). Such a long distance of propagation of reverse faults through the clastic sedimentary rocks of Paleozoic age is very unlikely, according to the discussion above. However, it is possible that the steep faults existed within the Triassic-Jurassic sequence, which behaved as a pseudo-basement at depth of 1-3 km, before the development of the monoclines. During reactivation in Senonian age, the faults propagated only short distances into the Lower Cretaceous rocks, and thus are not exposed today. This suggestion, that the reverse faults in the northern Negev propagated from a sedimentary pseudo-basement, does not exclude the possibility of large reverse faults in the deep crystalline basement. However, such deep faults would have a relatively small effect on the monoclines, compared to the shallow faults in the pseudo-basement.

This mechanical model is in good agreement with a tectonic model for Israel, suggested by Freund *et al.* (1975). They proposed that, during Triassic-Jurassic time, the region of Israel was subjected to regional extension in a WNW-ESE direction, and long basins (probably bounded by normal faults) developed during this stage (Fig. 8a). This old extensional field was replaced by a new regional tectonic compression, in WNW-ESE direction, in the Senonian. This new tectonic stress has been recorded (Fig. 7, Table 2). According to Freund *et al.*, the new tectonic stress reactivated the steep normal faults as reverse faults, and generated the large monoclines (Fig. 8b). Therefore, the "reversal of structure" model of Freund *et al.* (1975), is the most likely

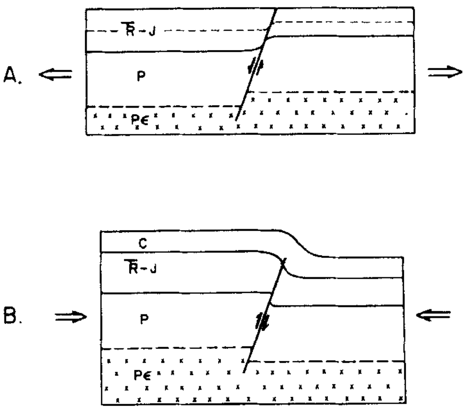

Fig. 8. Schematic presentation of the "reversal of structure" model for a monocline in the northern Negev (following Freund *et al.*, 1975). PC—Precambrian crystalline basement, P—Paleozoic, T-J—Triassic-Jurassic sequence, C—Cretaceous.

A—extension phase during Triassic-Jurassic age; B—compressive phase of Senonian-Eocene age. Note reversal of separation along the main fault, and negligible propagation of the fault into the Cretaceous rocks.

mechanism to explain the main features of the reverse faults in the Negev: large throw at shallow depth, no surface penetration, steep planes of the faults and the close occurrence of normal and reverse faults.

The Hebron monocline is similar structurally to the monoclines of the Negev, both in gross shape and internal strain. Thus, a reasonable assumption is that the reverse fault under the Hebron monocline has similar characteristics to the reverse faults under the Negev monoclines. The main parameters of the Hebron fault are described below.

1 The inclination can be estimated as follows: the horizontal shortening provided by the Hebron fault in the "pseudo-basement" of the Triassic-Jurassic rocks is accommodated in the upper levels by both monoclinal flexing and internal strain. During early stages of monocline development, the horizontal shortening provided by the reverse fault exceeds the shortening accommodated by monoclinal flexing (Freund, 1979), and the additional horizontal shortening is probably absorbed by compressional internal strain of the rocks. However, during later stages of development, the horizontal shortening associated with the monoclinal flexing exceeds the shortening provided by the steep reverse fault (Freund, 1979). At this stage, extensional internal strain develops in the anticlinal bend (Reches and Johnson, 1978). Evidence of extensional internal strain was only found in the proximity of Sections H-I (Fig. 1). As these sections have the largest uplift in the Hebron monocline (Table 1), it is concluded that these sections reached the later stages of monocline development. Following Freund (1979, Eq. 6), one can calculate the inclination, β, of a reverse fault for the stage that the shortening due to faulting equals the shortening due to flexing:

$$\beta = \arctan \frac{1-\cos\delta}{\delta-\sin\delta}$$

where δ is the maximum dip in the monoclinal flexure. Thus, for the Hebron monocline, with $\delta = 50^\circ$, the maximum inclination of Hebron fault is 73°. It should be noted, however, that the inclination of the fault may change with depth (e.g. Mimran, 1976).

2 The total throw of the Hebron fault at great depth should be approximately equal to the uplift of the host monocline, provided that no major dis-harmonic zones exist (Reches and Johnson, 1978). Thus, it is estimated that under Sections H-I, the lower layers of the Jurassic, at a depth of 4.0 km below sea level (m.s.l.), are offset by 1.2 km. If the model is correct, the throw should decrease gradually, and is expected to be replaced by a closed intense flexure. The fault is inferred to terminate at the base of the Lower Cretaceous beds.

3 The lateral location of the postulated reverse fault is less restrictive than the vertical variation. In the northern Negev, for example, the reverse faults can be located laterally between the anticlinal bend and the kinked zone for four of five faults found in the monoclines (Aharoni, 1976). Direct observations in monoclines of the western US locate the major faults under the anticlinal bend (e.g. Reches, 1978; Stearns, 1971). The consistency in location and altitude of the hinge zones in the Hebron monocline (Fig. 4), suggests that they are related to a single source, most likely the Hebron fault. Thus, it is suggested that the Hebron fault lies along the continuation of the kinked zone, H_Z, in the flexure (Figs. 4, 5). However, similarly to the Negev monoclines, this fault may be closer to the anticlinal bend.

Based on the study of the Hebron monocline, a subsurface structure for Section H, which runs through the Halhul-1 borehole (Fig. 5) has been delineated, and its main features are as follows: the Hebron fault is located within a zone of 1 km width, inclined at about 73°, under the "mismatch" zone of the monocline (Fig. 5). The layers above the fault are slightly folded and dip gently, and those west of the fault are intensely flexed in the proximity of the fault, with an open synclinal bend further to the west. The throw along the main fault decreases from about 1.2 km at 4.0 km below m.s.l. to zero at about 0.2 km below m.s.l. Normal faults with displacement of a few tens of meters may be found in the proximity of the reverse fault.

In the present study the subsurface structure has been determined by construction of accurate surface traverses across the elongated monocline. The modified Busking method (Appendix), seems to be a reliable, simple technique of lineation of both surface as well as subsurface structure. For example, the crestal zone in Section H (Fig. 5) is practically vertical; thus, drilling for crestal traps here should be on the surface crest, rather than down-dip on the uplifted block. The Halhul-1 borehole is located at the crest of Section H (Fig. 5); however, the highest point along the crest is at Section I, about 2 km south of Section H (Figs. 1, 3).

Another structural trap could exist in the downthrown block at the proximity of the reverse fault (e.g. Levorsen, 1967, Ch. 6). However, due to the great difficulty in locating this fault, the choice of well location for such a trap requires more information on the subsurface structure.

ACKNOWLEDGEMENTS

Discussions with numerous colleagues have contributed to this study. Our thanks go to I. Shachnai, U. Bieda, Y. Arkin, Y. Eyal, E. Diamant, H. Fligelman and particularly to the late R. Freund. Y. Eyal kindly let us use some of his unpublished data, and the technical assistance of S. Fliegelmann and Y. Barbut is greatly appreciated.

This study was supported by a grant from the Ministry of Energy and Infrastructure, Israel.

APPENDIX

The modified Busking method

The Hebron monocline is a long structure; due to its high length/width ratio, the structure is assumed to be essentially two dimensional, and thus its gross shape can be studied through accurate cross sections. The sections have been constructed using the following method (Fig. 5): field measurements of stratigraphic contacts and dips along traverses sub-normal to the main monocline were plotted at a scale of 1:20,000. The author's own measurements together with the results of Arkin (1978), Kolton (1972) and Gilat (1977) have been used. As thickness variations in the Judea Group due to deformation are negligible (Hirsch, *in prep.*), the concentricity of the flexure and the lack of major disharmony in the deformed Cretaceous units have been assumed. In the modified Busking method, *several* concentric arcs are fitted to many stratigraphic contacts and dips projected on to the cross section (Fig. 5). This is done by applying an overlay traced with many concentric arcs over the section, and searching for the arcs that fit as many data points as possible. The centers of the best fits are marked (R_1, R_2 and R_3 in Fig. 5), and concentric arcs are constructed with a compass.

In the common Busking method, a center for the concentric arc is taken between every two neighbouring data points, thus implicitly assuming that there are no measurement errors and no natural deviation between the points. On the other hand, by the present method a search is made for best-fit centers, and large, consistent zones of concentricity are obtained.

REFERENCES

AHARONI, E., 1976. The surface and subsurface structure of the southern Judean desert, Israel. Library of the Israel Geol. Surv., Jerusalem, 100 p. (Hebrew with English summary, unpublished report).

ARKIN, Y., 1976. Geological Map, Jerusalem and Vicinity. Geol. Surv. Israel, Scale 1:50,000.

COATES, J., GOTTESMAN, E., JACOB, M. and ROSENBERG, E., 1963. Gas discoveries in the western Dead Sea region. *Proc. 6th World Petrol. Cong.*, Frankfurt, **1**, Paper 26.

COOK, P., 1971. A columnar section of the Judea Group (Cretaceous) west of Hebron. Geol. Surv. Israel, Rept. No. M.M. 100/7/0.

FREUND, R., 1965. A model of structural development of Israel and adjacent areas since Upper Cretaceous times. *Geol. Mag.*, **102**, 189-205.

FREUND, R., GOLDBERG, M., WEISSBROD, T., DRUCKMAN, Y. and DERIN, B., 1975. The Triassic-Jurassic structure of Israel and its relation to the origin of the Eastern Mediterranean. *Geol. Surv. Israel Bull.*, **65.**

FREUND, R., 1979. Progressive strain in beds of monoclinal flexures. *Geology*, **7**, 269-271.

GILAT, A., 1977. Geological Map, Eshtemoa. Geol. Surv. Israel, Scale 1:50,000, Sheet 15-I.

HARDING, T. P. and LOWELL, J. D., 1979. Structural styles, their plate-tectonic habitats, and hydrocarbon traps in petroleum provinces. *Amer. Assoc. Petrol. Geol. Bull.*, **63**, 1016-1058.

HENSEN, F. R. S., 1951. Observations on the Geology and Petroleum Occurrences of the Middle East. *Proc. 3rd World Petrol. Cong.*, **1**, 118-140.

KOLTON, Y., 1972. Geological Map, Hebron Region. TAHAL Consulting Engineers, Ltd., Tel-Aviv, Scale 1:20,000, unpublished.

KRENKEL, E., 1924. Der Syrische Bogen. *Centralbl. Mineral.*, **9**, 274-281, and **10**, 301-313.

LEVORSEN, A. I., 1967. Geology of Petroleum. Freeman and Co., 724 p.

MIMRAN, Y., 1976. Deep-seated faulting and the structures of the northern Negev (Israel). An Analytic and Experimental Study. *Israel Journ. Earth Sci.*, **25**, 111-126.

RECHES, Z., 1978. Development of monoclines: Part I. Structure of the Palisades Creek branch of the East Kaibab monocline, Grand Canyon, Arizona. *In:* MATTHEWS, V., III, 1978. Laramide Folding Associated with Basement Block Faulting in the Western United States, *Geol. Soc. Amer. Mem.*, **151.**

RECHES, Z. and JOHNSON, A. M., 1978. Development of monoclines: Part II. Theoretical analysis of monoclines. *In:* MATTHEWS, V., III, 1978. Laramide Folding Associated with Basement Block Faulting in the Western United States, *Geol. Soc. Amer. Mem.*, **151.**

RECHES, Z. and EYAL, Y., 1979. Regional distribution of paleostress in the vicinity of the Dead Sea Rift, Israel (abs.) *Amer. Geophys. Union. Trans.*, **60,** 948.

ROFE and RAFFERTY, Consulting Engineers Ltd., 1963. Jerusalem and District Water Supply. Geologic and Hydrologic Rept., London (unpublished).

STEARNS, D. W., 1971. Mechanism of drop folding in the Wyoming Province. Wyoming Geol. Assoc., 23 Ann. Field Conf., Guidebook, 125-143.