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Joints and en échelon cracks in Middle Eocene chalks near Beer Sheva, Israel

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Abstract—Planar vertical joints and straight en échelon cracks are closely associated in an erosional exposure of Middle Eocene chalks in a syncline south of Beer Sheva. The two dominant joint sets are oriented 357° (N3°W) and 031° (N31°E) and both sets occur in two separate outcrops 400 m apart. An en échelon crack array accompanies each joint set. The individual en échelon cracks are oriented 337 and 053°, respectively. Radial plumose markings are present on the surfaces of the en échelon cracks. They imply that fracture occurred normal to a local tensile stress axis. A gradual rotation of the azimuths of the joints and cracks occurs between the two outcrops; this rotation implies jointing due to NNE–SSW compression and en échelon cracking due to unloading of this compression.

INTRODUCTION

Arrays of en échelon crack segments formed in a variety of materials emerge in numerous ways from the peripheries of fractures at scales ranging from μm to km. This ubiquity suggested the possibility of several mechanisms of origin to Pollard *et al.* (1982), who investigated the mechanism of initiation and growth of dilatant en échelon cracks. They concluded that incipient en échelon cracks form at the parent-crack tip normal to the local maximum tensile stress direction. Longitudinal growth (along surfaces that twist about axes parallel to the propagation direction) realigns each en échelon crack into a remote principal stress phase. The important implication is that dilatant en échelon cracks are generally parallel to a principal stress direction. Shainin (1950) studied the regional distribution of dilatant en échelon cracks at Riverton, Virginia. He found that the en échelon cracks were aligned in two fairly straight conjugate rows that intersected at an acute angle which was bisected by the horizontal greatest principal stress. However, Shainin's results (1950, fig. 1) do not show that the individual en échelon cracks formed parallel to a remote principal stress. Work by Lajtai (1969), Hancock (1972) and Rickard & Rixon (1933) has demonstrated additional aspects of the complex mechanisms involved. The difficulties are further compounded by the observation that some extensional fractures (joints with plumose markings on their surfaces) are aligned along conjugate shear directions, rather than being parallel to principal stresses (e.g. Muehlberger 1961). More basic information is required for a deeper understanding of these fundamental problems. Some new field observations relevant to the subject are presented here.

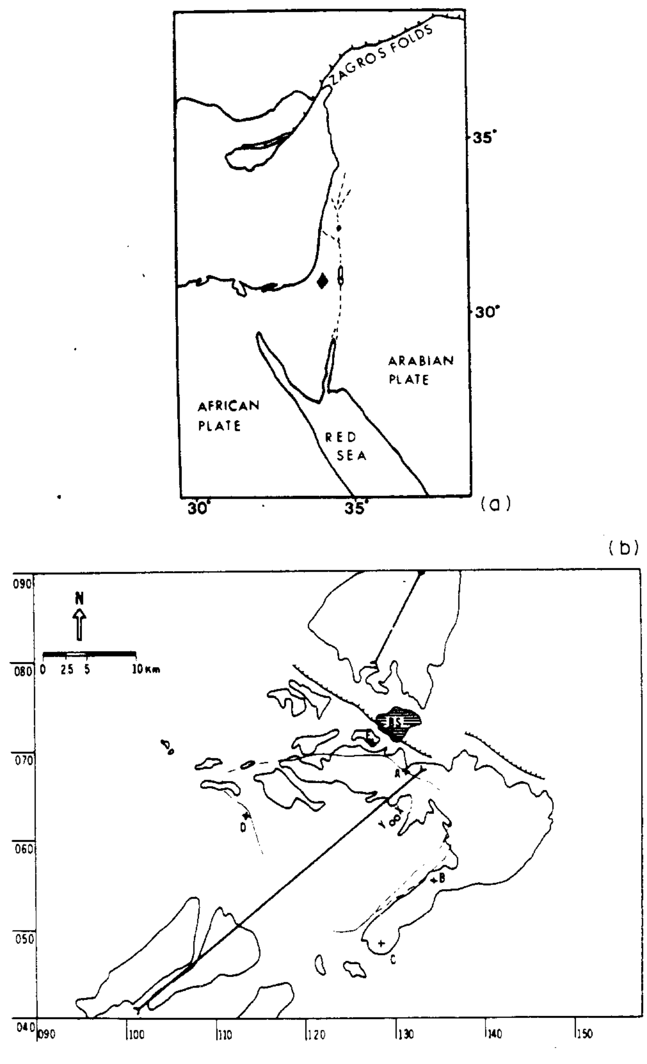


Fig. 1. (a) Location map. The study-area is indicated by a rhomb in which the town of Beer Sheva is approximately located at the centre. (b) Map of study-area. Heavy lines mark the boundaries of exposed Eocene rocks (after Bentor *et. al.* 1970) in two synclines north and south of Beer Sheva (BS). Light line (partly dashed) is a boundary between Lower and Middle Eocene rocks. *X* and *Y* are main outcrops of the present study, and *A–E* are outcrops of low-angle normal faults (Bahat 1985). Barbed lines are inferred faults south of Beer Sheva (after Gvirtzman 1969).

GEOLOGICAL SETTING

Subvertical en échelon crack arrays that accompany vertical joints may occasionally be found in chalks of the

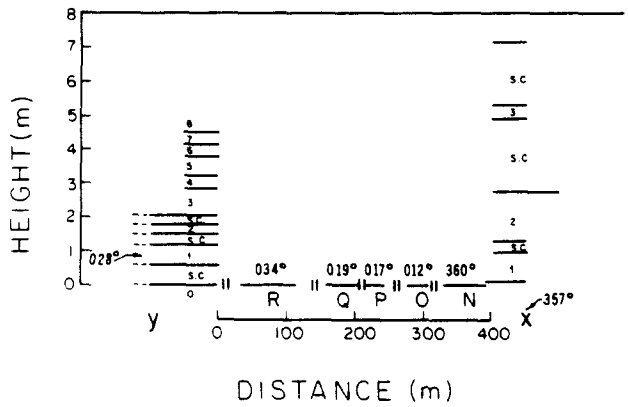


Fig. 2. Outcrops X and Y including floors N to R between them showing rotation in mean azimuths of joints from 357 to 028°. Numbers 1–3 in X and 0–8 in Y designate hard chalk layers in vertical sections. Beds of soft chalk (s.c.) alternate with some of the hard chalks. In Y, beds 0–2 and alternating *s.c.* occur also as platforms in horizontal sections. The two close small vertical lines between floors N and Y represent talus.

Table 1. Joints and en échelon cracks in vertical sections at outcrop X

Layers	Lower	Middle	Top
Layer thickness (cm)	100	~150	45
Azimuth of joint (°)	014	350	354
Thickness (cm) of planar region T	25	14	11
Length (cm) of small en échelon cracks above planar region	—	10	10
Mean azimuth of small en échelon cracks above planar region (°)	—	345	343
Length (cm) of small en échelon cracks below planar region l	10	10	8
Mean azimuth of small en échelon cracks below planar region (°)	340	342	338
Length (cm) of large en échelon cracks below planar region L	40	25?	16
Mean azimuth of large en échelon cracks below planar region (°)	342	341	338
Ratio L/T	0.4	0.7	0.7
Ratio L/T	1.6	1.8?	1.4

Mean azimuth determinations for en échelon cracks represent 2–4 measurements. The joint appears as the planar region on a vertical section and as the main crack on a horizontal section (Table 2). In the middle layer the lower boundary of large en échelon cracks is not clear.

Table 2. Characterization of joints and en échelon cracks in horizontal section at outcrop X

Fractures from west to east	1	2	3	3	4	5	6	7
Azimuth of main crack (°)	353	008	010		010	353	005	011
Length (cm) of main crack	780	470	1250		1000	1100	930	500[15]
Number of en échelon cracks (N)		9	14	7	3	9	1	9
Mean azimuth (°) en échelon cracks (N)		333(2)	333(1)	344(8)	337(2)	333(3)	331	337(3)
Max. width (mm) en échelon cracks		180	150	55	23	110		110
Min. width (mm) cracks (N)		5	50	16	18	40		50
Mean step (mm) between en échelon cracks (N)		23(11)	22(11)	16(9)	9(1)	15(6)		13(6)
Mean azimuth en échelon branch (N)			003	012	351	358		004
Length (mm) en échelon branch (N)	380		500	300	70	470		670
Twist angle (°) between main and mean en échelon cracks (N)	35		37	26	33	20	34	34[18]
Number of en échelon cracks (S)			7		10			
Mean azimuth (°) en échelon cracks (S)			340(4)		343(6)			
Max. width (mm) en échelon			210		105			
Min. width (mm) cracks (S)			47		46			
Mean step (mm) between en échelon cracks (S)			56(23)		17(6)			
Mean azimuth (°) en échelon branch (S)			015		007			
Length (mm) en échelon branch (S)			770		550			
Twist angle (°) between main and mean en échelon cracks (S)			30		27			

Two sets of figures for fracture 3 represent the two en échelon branches. Numbers in square brackets for fracture 7 represent a second branch of the main crack. (N) and (S) indicate north and south sides of the main cracks, respectively. Values for mean azimuth of en échelon cracks and mean step lengths are presented with the standard deviations on their right-hand sides. These measurements were carried out on a subhorizontal floor. Due to the small inclination of the floor (see text) parameters of en échelon cracks should be treated with appropriate caution.

Table 4. Rotation of Joints and en échelon cracks.

Outcrop	Mean azimuth°	Standard deviation°	Number of measurements°	Mean azimuth°	Standard deviation°	Number of measurements
X	357	12	63	337	6	91
N	360	4	25			
O	012	5	36	026	5	6
P	017	3	28			
Q	019	2	27	039	2	5
R	034	5	52			
$Y1$	028	1	21	053		
$Y2$	028	3	26	053	11	68
$Y3$	035	8	24	053		

$Y1$, $Y2$, $Y3$ represent platform 1, platform 2 and layers 3–8 in Fig. 2, respectively.

Table 3. Azimuths of en échelon cracks and steps in a horizontal section at outcrop *X*

Fracture 2(N)		Fracture 3(N) western region		Fracture 3(N) eastern region		Fracture 4(N)		Fracture 5(N)		Fracture 7(N)		Fracture 3(S)		Fracture 4(S)	
A°	2s (mm)	A°	2s (mm)	A°	2s (mm)	A°	2s (mm)	A°	2s (mm)	A°	2s (mm)	A°	D (mm)	A°	D (mm)
335	6	333		359	7	339	10	330	17	339	11	340	64	346	
336	35	333	8	354	8	337	8	334	11	339	8	346		349	8
331	19	334	13	340	7	335		332	8	330	11	344	48	348	8
333	17	333	23					331	17	333	9	341	54	349	20
335	20	333	8	340				329	12	334	6	339	94	350	12
331	17	335	23	338	15			334	20	340	24	337	15	343	14
334	14	331	25	339	25			337	23	339	14	335	60	340	18
331	44	331	10	338	30			334	23	337	23			336	20
335	33	332	22					337	15	339				337	25
		335	37											334	25
		331	30												
		332	11												
		332	32												
		333	40												
Mean: 333 ± 2	23 ± 11	333 ± 1	22 ± 11	344 ± 8	16 ± 9	337 ± 2	9 ± 1	333 ± 3	15 ± 6	337 ± 3	13 ± 6	340 ± 4	56 ± 23	343 ± 6	17 ± 6

A° signifies azimuth of en échelon cracks and step 2*s* is the distance between adjacent en échelon cracks.

Table 5. Size parameters of en échelon cracks

Outcrop	*X*	*X*	*X*	*O*	*O*	*O*	*O*	*Q*	*Q*	*Q*	*R*	*R*	*R*	*R*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*
Layer	1	2	3								1?	1?	1?	1?	1	1	2	5	5	5	5	5
Joint number	1	2	3	4	5	6	6	7	8	8	9	9	10	11	12	12	13	14	15	16	17	18
Planar crack azimuth (°)	010	350	357	021	009	006	006	026	019	019	042	042	039	039	032	032	028	335	032	031	035	028
En échelon crack azimuth (°)	344	343	337			033	020	039			054	054		071	057	057		327	051	040	053	045
Twist angle	26	7	20			27	14	13			12	12		32	25	25		8	19	9	18	17
Large en échelon cracks																						
length (cm)	22	15(12)	10(10)	2	4		28	15		6		65	4.5	12		40	7(4)	7	15	7	17(17)	30(30)
width (cm)	16	10(2)	4(2)	2	3		9	9		3		30	1.5	3		10	3(1)	3.5	9	1.5	11(5)	13(6)
step (cm)	6	2(0.5)	1.5(0.5)	0.4	2.5		1.5	1.5		1		7	0.4	4		3.5	1.5(0.5)	0.5	1.5	0.5	2(1)	2(0.5)
Small en échelon cracks																						
length (cm)	9					3			3		30				8(4)							
width (cm)	2					2.5			0.7		10				4(2)							
step (cm)	3					0.5			0.6		3.5				1.5(0.4)							

For additional details see data on outcrops and layers shown in Fig. 2. En échelon cracks are presented with specific associated joints. Free numbers generally represent maximum size values and adjacent numbers in brackets are minimum values for cracks of the same series.

Lower and Middle Eocene in the Shephela and Beer Sheva synclines north and south of the town of Beer Sheva, respectively (Bentor & Vroman 1963, Braun 1967). The folds are typical of those along the Syrian Arc in Israel. The en échelon cracks are common in a strip, about 950 m long, in chalks of Middle Eocene age (Horsha formation) of Wadi Naim, some 9 km south of Beer Sheva (Fig. 1). Although joints are common throughout the formation, en échelon cracks are largely confined to the strip studied.

The cracks are particularly abundant in two outcrops, some 400 m apart, here labelled *X* (to the NE) and *Y* (to the SW) (Fig. 2). The outcrops reveal the structures in chalk both on vertical exposure walls and on adjacent floors. Five outcrops of rock platforms (at wadi level) alternate along the 400 m wadi with patches of talus between exposures *X* and *Y* (Fig. 2). The talus obscures any stratigraphic continuity, but the slope of the wadi towards the southwest is very moderate (1° or less) and the chalk beds are almost horizontal. Additionally, the vertical throws on each of the three exposed normal faults in the area (at exposure *Y*) are less than 1 m. Therefore, even if faults are buried beneath talus it is assumed that the various outcrops examined, including *X* and *Y*, are not more than several metres apart stratigraphically. The present study characterizes the fracture associations in exposures *X* and *Y* and in the five platforms between them. Field data are summarized in Tables 1–5, and the terminology of Pollard *et al.* (1982, figs. 2 and 11) is adopted.

PLANAR JOINTS AND EN ÉCHELON CRACKS IN OUTCROP *X*

Outcrop *X* trends roughly N–S along an unpaved road. Here joints trending N–S are exposed along a quarried vertical wall and in an adjacent platform. The platform is also crossed by additional fractures oriented 069 and 030°. Integrating the vertical and horizontal features permits the three-dimensional geometry of the en échelon cracks to be inferred. Occurrences of such geometries are rare (Pollard *et al.* 1982).

Surface morphology of fractures on vertical exposure surfaces

The fracture surface is exposed in three hard chalk layers separated by beds of soft chalk and gypsum (Fig. 2). Hard layers vary in thickness from 45 to 150 cm (Table 1). Each fracture may be divided into three distinct zones, a middle zone characterized by a planar crack is sandwiched between two zones of en échelon cracks (terminology in Fig. 3). The planar joints are commonly straight, but occasionally they are wavy and hence show variations in strike. The planar joints with delicate plumose markings indicate that such cracks propagated horizontally (trending approximately north or south). These plumes are of axial type and straight (Bahat & Engelder 1984).

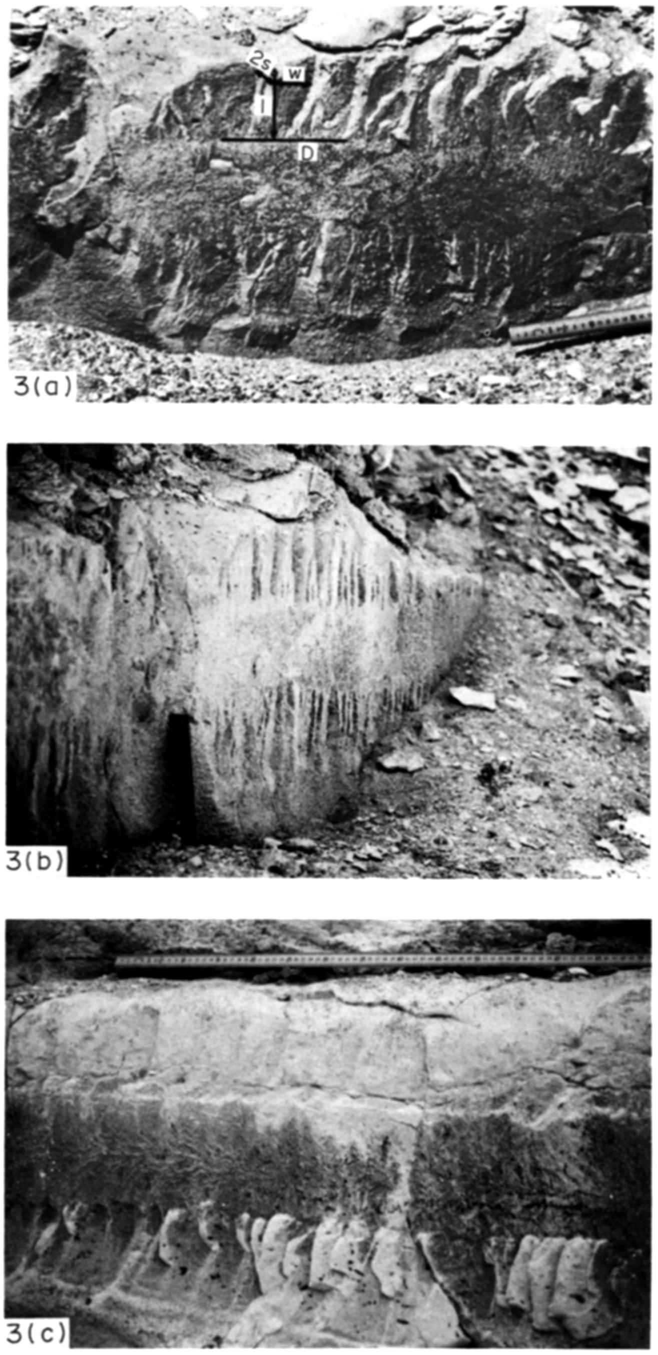
Often the en échelon cracks occurring below the planar zone are larger than those above. The en échelon cracks have a constant angular relationship with the planar fracture. Information on three successive hard chalk layers is summarized Table 1. In each layer the character of the en échelon region is somewhat different. Large en échelon cracks below the planar zone may be well developed. They appear in a few locations below small en échelon cracks, whereas at other sites the large en échelon cracks are developed immediately below the planar zone. In all cases, small and large en échelon cracks maintain about the same azimuth and the transition from the planar to the en échelon zone is discontinuous. There are no gradual changes from one type of crack to another.

Surface morphology of fractures on horizontal exposure surfaces

A series of seven subparallel traces of vertical fractures trending roughly N–S are exposed on a chalk platform which is a continuation of the middle layer of hard chalk at the wall (layer 2 in Fig. 2). Due to erosion the surface of this platform is inclined 10° towards the south. Each fracture consists of a single main crack. In addition, most main cracks branch at their tips into zones of straight en échelon cracks (Fig. 4, Tables 2 and 3). The seven main cracks vary in azimuth between 353 and 011°. The orientation range of the en échelon cracks is between 331 and 352°. The azimuths of the main cracks vary within a range of 18°, and the range of the twist angles produced by the main and mean en échelon cracks is 17°. However, the angular variation of the mean azimuth of all the en échelon cracks on the northern side of the platform (with the exception of the 012° branch of fracture 3) is only 5°. This suggests that the azimuth and twist angles of the en échelon cracks were not influenced by the orientation of the individual main crack, but rather by a different process (perhaps areal) which acted more uniformly than could be expected from the spread of orientations of the main cracks.

At the southern extension of fracture 3 there are two en échelon cracks which are oriented 019 and 020°. Also, there are two somewhat distorted cracks (S shapes) that are oriented 012 and 011° south of fracture 4.

The detailed measurements of azimuths of individual en échelon cracks and steps (normal distances) between them (Table 3) show that at the northern tips of several main cracks there is no systematic change in crack orientation with distance from the tips (fracture 2, the western en échelon region of fracture 3, and in fractures 5 and 7). On the other hand, there seems to be a gradual anticlockwise change in azimuth at the eastern en échelon region of fracture 3, and in fracture 4. There is also a somewhat consistent trend of increasing steps between en échelon cracks with distance from the main crack tip. This is particularly clear in the eastern crack region of fracture 3, fracture 7 and fracture 5. Gradual anticlockwise rotation of cracks can also be observed at the southern tips of fractures 3 and 4, and increase of steps



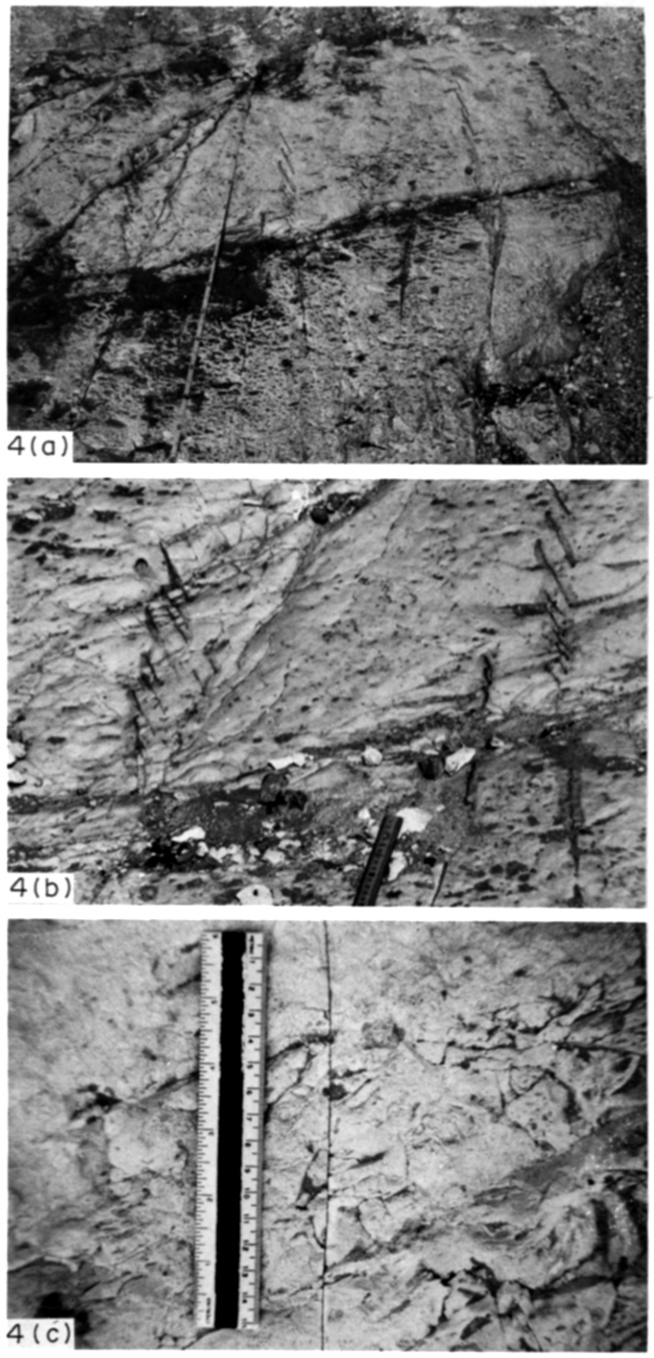
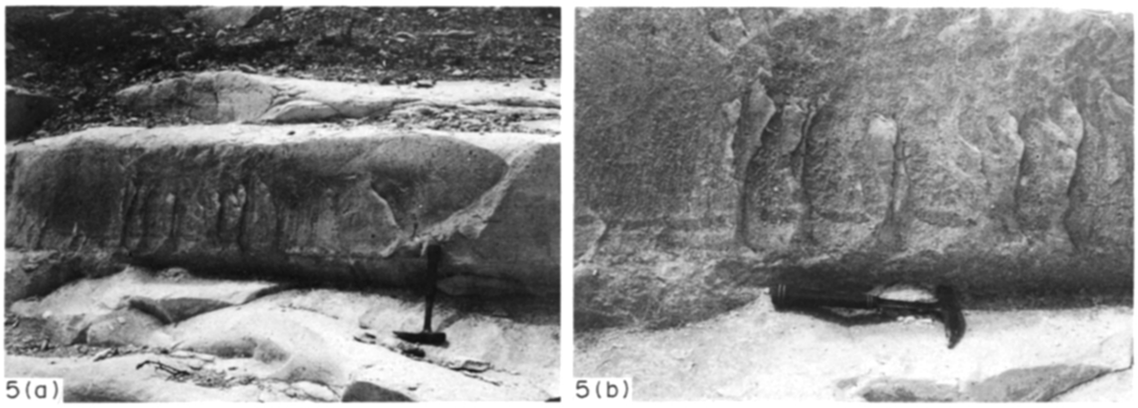
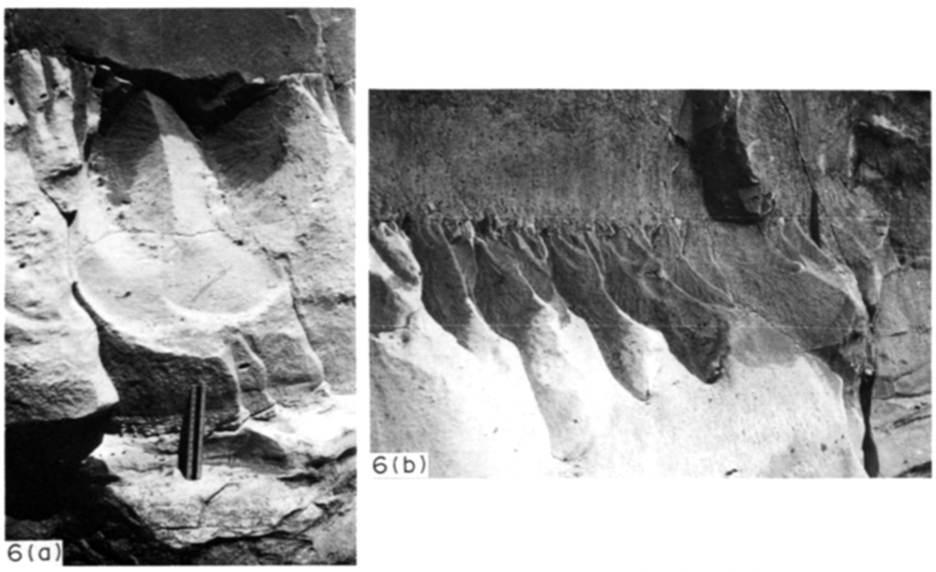


Fig. 3. Vertical joint with a planar region at the centre, and en échelon zones above and below it. (a) Line D is a discontinuous boundary between the upper en échelon cracks and planar fracture, l is length, w is width and $2s$ is a step (i.e. thickness) of an en échelon segment (note cm scale). (b) Note differences in size of adjacent segments that maintain the same orientation (black scale is 15 cm long). (c) Note a delicate horizontal plumose mark on a planar surface of uniform thickness (outcrop X, middle layer, Fig. 2) and en échelon regions above and below it (the former being partly eroded) and a scale of 70 cm length are shown as well.

Fig. 4. (a) A part of platform 2 in outcrop X contains fractures 3–7 (from left to right). Fracture 3 (left of the scale) branches into two en échelon zones on its northern side. (b) Northern sides of fractures 3, 4 and 5. The portion of scale in picture is 15 cm long. (c) A part of a main crack showing the lack of any indication of strike-slip offset. Scale is 15 cm.





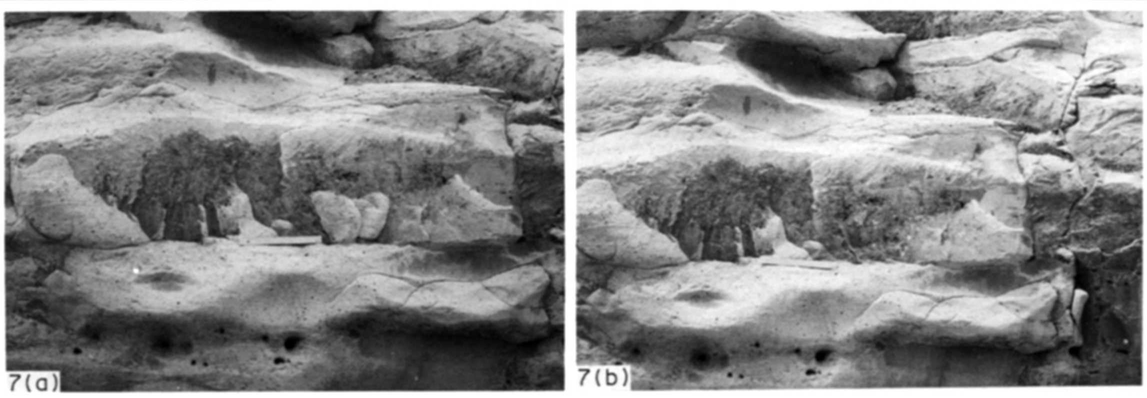


Fig. 5. A joint surface at outcrop *Y* with an undulating strike and a delicate bilateral plumose mark. (a) En échelon cracks are concentrated at the centre of the joint where the strike is 028° and they become fewer towards the edges where the strike is 046°. Note the continuous transition from the planar joint to the en échelon segments. (b) A close up of rhythmic relationship between vertical en échelon cracks and horizontal segments of rib-marks (dark lines).

Fig. 6. Delicate radial plumose markings on the surfaces of en échelon cracks below a planar joint. (a) Two adjacent en échelon cracks with radial plumes (note that propagation was upward, downward and laterally to the left). Scale is 15 cm. (b) Main propagation direction was vertically downward. Note the concentric arrest line (rib-mark) in the lower part of a plume.

Fig. 7. Two adjacent joints from outcrop *Y* with separate plumes that propagated in opposite directions. (a) Before removing two en échelon segments (flakes at right side of 30 cm scale). (b) Irregular scars after removal of the two flakes, indicating that there was not a planar joint behind the en échelon cracks.

Fig. 8. Joints oriented 017° in floor *P* (see Fig. 2). Width of dark rectangle in the centre of the photograph is 23 cm long.

between en échelon cracks with distance from the main crack tip occurs in fracture 4, but not in fracture 3. These changes imply that a few main cracks exerted an influence on later en échelon cracks while others did not. It is not clear what controlled this change. In most fractures on the platform (Table 3) en échelon cracks are fairly uniformly oriented (333°). At the wall exposure (Table 1) there are deviations from this trend. The absence of cracks oriented 011–012° at the northern tips of the main cracks and their limited appearance close to the southern tips indicate that there were unfavorable conditions for their development. Furthermore, their deformation possibly indicates a late stage development (Tchalenko 1970) but necessarily associated with the main fracture event of the straight en échelon cracks.

Significantly, a close examination of the traces of the main cracks indicates that they are smooth (although not exactly straight) and are not distorted along the planes of fractures (Fig. 4). Hence, no displacement along the main cracks is recognized.

In summary, there appear to be wide ranges of orientation for the main cracks and en échelon cracks at exposure *X* and around it. The respective mean azimuths are 357 ± 12° (63) (i.e. 63 measurements, ±12° population standard deviation) and 337 ±6° (91). Associated with these fracture systems are a few en échelon cracks that vary in orientation from 011 to 041°. These cracks are generally somewhat distorted; possibly implying late local shearing. Generally, the joints seem to exert only limited influence on the orientations and the size parameters of the en échelon cracks associated with them.

PLANAR JOINTS AND EN ÉCHELON CRACKS IN OUTCROP *Y*

One joint set dominates the outcrop (which is about 230 m long) and its vicinity. The azimuth of this set exposed in two platform beds is almost uniform (028 ± 2° (47)) but a considerable spread (035 ± 8° (24)) is observed on the adjacent wall (Fig. 2). The range is partly due to actual variations in azimuth and occasionally a result of curving fractures. The weighted mean of all measured joints in the two platforms and cliff is 031 ± 7°. Straight plumose markings are common on the joint surfaces of the set striking 031°.

En échelon cracks oriented 053 ± 11° (68) commonly occur in the lower parts (but not in the upper parts) of the 031° striking joints in hard chalk beds where they are exposed on the platform and in the cliff. Occasionally, these en échelon cracks also cut through the upper parts of the soft chalk beds that alternate with the hard chalk underlying floors.

In bed 5 of the cliff (Fig. 2) a curved fracture is represented by a joint, 1.5 m in horizontal length and is almost 0.5 m high (Fig. 5). Delicate plumose marks cover almost the entire surface of the joint. Delicate plumes are the only plumose style observed on joints of sets striking 031 and 357° in the investigated area. They are quite different from markings which occur on joints in Lower Eocene chalks of the region (Bahat 1985). The joint illustrated in Fig. 5 curves from an orientation of 046° at its northeastern end to 028° at the centre and back to 046° at its southwestern end. However, the en échelon cracks along the entire length of the joint maintain an almost uniform azimuth of 044–047°. At the centre of the joint (along a stretch of azimuth 028°) the concentration of en échelon cracks is higher than close to the horizontal edges of the fracture, indicating a preference for maintaining an angular relationship between a planar fracture and en échelon crack (rather than subparallelism between the two types of failure surfaces).

The elongate series of joints of set 028° in the hard chalk beds in the platforms, appear much shorter (1 m or less) and they are often irregular and isolated in the soft chalk beds that alternate with them. En échelon cracks that occur in the soft chalks maintain a uniform orientation of 053°. These cracks are accompanied occasionally by another set of en échelon cracks oriented (342±7° (9)). The latter are less regular and characteristically propagated towards the 053° set, suggesting that the 342° set fractured after the 053° set.

At the eastern end of outcrop *Y* there is a large fracture in platform 1. The fracture is slightly curved (azimuths vary from 028 to 035°). There is a delicate plume of 2.35 m length on the planar fracture. Below this plumose zone there is a series of en échelon cracks of 40 cm maximum length. The cracks vary in strike from 056 to 059°. Some of them dip 85° to the southeast. Especially impressive are a few en échelon cracks that reveal plumose markings (Hodgson 1961a, fig. 1) generally of radial pattern (Fig. 6). This suggests that the en échelon cracks are at least partly of dilatant origin. Barely noticeable plumes occur on surfaces of other en échelon cracks.

TRANSITIONS FROM PLANAR TO EN ÉCHELON CRACKS

En échelon cracks in vertical sections at outcrops *X* and *Y* always occur above or below the planar main fracture, that is en échelon cracks occur close to bed boundaries. This observation implies that all en échelon cracks were formed after planar main fractures. In outcrop *X* the transition between the planar fracture and the en échelon cracks is always discontinuous (Fig. 3), whereas in outcrop *Y* the transition although most commonly discontinuous is occasionally continuous. Typical of continuous transitions is the upward penetration of en échelon cracks to the planar region above it. Here, one would expect that if there had been a time interval between an early dilatant fracture and the younger en échelon cracks, the latter cracks would perhaps intersect existing planar surfaces behind them. When the writer removed various en échelon flakes from such structures he uncovered irregular surfaces (Fig. 7). This demonstrated that planar dilatant cracks did not exist behind en échelon cracks. Furthermore, it suggested

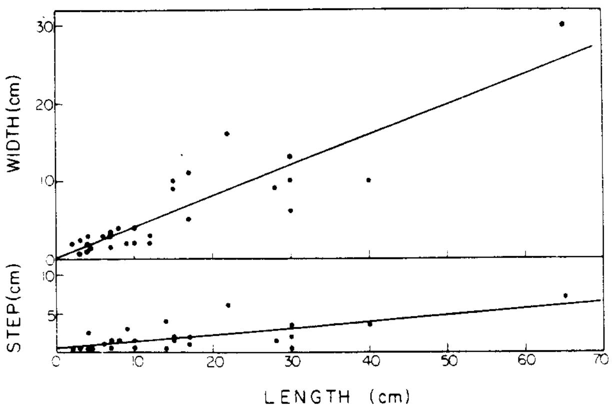


Fig. 9. Size parameters of en échelon cracks (also see Table 5), length vs step (below) and length vs width (above).

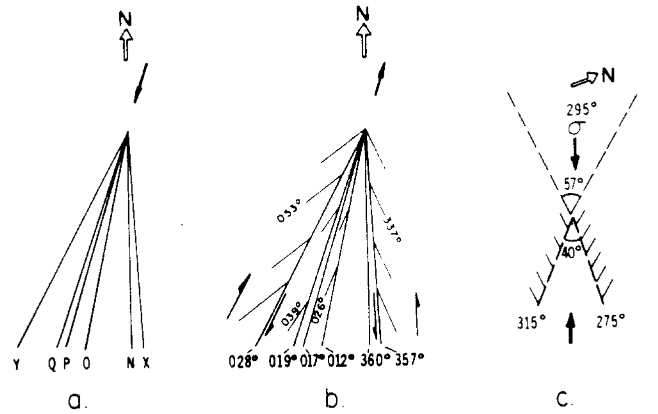


Fig. 10. Orientation of joints and en échelon arrays. (a) Joint rotation in six adjacent outcrops (see Fig. 2) and implied compression direction. (b) Azimuths of rotated joints and en échelon cracks in six outcrops. Directions of shear stresses and elongation are derived from the orientation of the en échelon cracks (outcrops *X* and *Y*). (c) Two conjugate en échelon arrays and the inferred compression direction (after Shainin 1950).

that the process of failure from early planar fracturing to en échelon cracking was continuous (see also Fig. 5a). In addition, there is a clear harmony between the en échelon flakes and segments of a large rib-mark (Fig. 5b), the latter representing fracture fronts of en échelon cracks that propagated vertically downwards. They imply a linked development of en échelon cracks and fracture surface markings. Hodgson (1961a, figs. 1a & b, and fig. 23) described joint fringes in which certain ridges of the plume curved and terminated in small en échelon cracks. Such transitions were not observed in the present study possibly because as a consequence of their delicacy plumes could not be traced to their termini.

It is possible that the processes of dilatant-planar and en échelon fracturing were dissimilar at outcrops *X* and *Y* along the 357 and 031° directions, respectively. There are differences in the modes of transition from planar fractures to en échelon cracks, the latter occurring both below and above planar fractures of set 357°, but occurring only below dilatant fractures of set 031°. This distinction may imply that the extensional fractures of set 031° propagated freely from the centre of the bed to its upper boundary, and therefore there was no room for the younger en échelon cracks to develop, whereas in the set striking 357° extensional fractures were confined to the centre of the bed.

PLANAR JOINTS BETWEEN OUTCROPS *X* AND *Y*

There are five chalk platforms that alternate with areas of talus along a 400 m strip between outcrops *X* and *Y*. Joint orientations were measured on all these floors along random traverses (Fig. 8). The mean results are marked above the positions of the platforms in Fig. 2. There is a gradual (clockwise) rotation of joint orientations between outcrops *X* and *Y* (Table 4). Evidently, floor *R* departs from the general pattern of rotation. This floor is possibly a continuation of floor 0 from outcrop *Y* and detailed measurements show that there is a slight shift in joint orientation from 38 ± 3.6° (29) on the eastern side to 32 ± 5° (23) on the western side of the floor. The reason for the exceptional behaviour of joints in this platform is not known. Although the majority of en échelon cracks in the investigated area are oriented close to 337 and 053° (in outcrops *X* and *Y*), there are a few exceptions with intermediate azimuths (Table 4, outcrops *O* and *Q*). Some of the latter may be up to 12 cm in length. The intermediate orientations suggest that the en échelon cracks are also rotated, presumably in sympathy with the rotation of the joints.

SIZE PARAMETERS OF EN ÉCHELON CRACKS

Size of en échelon cracks was determined in vertical sections at most outcrops, with the emphasis being given to three size parameters. They are: length of en échelon cracks, l, measured along their dip direction (approximately normal to bedding), width, b, measured parallel to the strike of the en échelon crack, and step, $2s$, the normal distance between two adjacent cracks (Fig. 3). The results (Table 5) enable several correlations to be made. (1) Occasionally, en échelon cracks appear to have propagated in stages. This is manifested by the occurrence of adjacent small and large en échelon cracks of fairly uniform size below the same planar crack. Close to the planar crack there is a series of small en échelon cracks, and below them larger en échelon cracks (fractures 1, 8, 9 and 12). Commonly, the orientation of the small and large en échelon cracks is identical. An exception is seen in fracture 6 (outcrop *O*) where the change in size also involves fracture rotation. (2) En échelon cracks (like plumose markings) show a preference for particular beds and are rarer in adjacent beds of similar lithologies. For instance, en échelon cracks (and plumose markings) are particularly common in layer 5 in outcrop *Y* (Fig. 2). (3) Although there are noticeable exceptions, en échelon cracks seem to increase in size with bed thickness. The en échelon cracks of fracture 13 are fairly small and uniform in size in platform 2, which is 30 cm thick, but they become consideraly larger in platform 1 (fracture 12) and bed 5 (fractures 15, 17, 18) which are both 60 cm thick. (4) There are some considerable differences in size of en échelon cracks even in adjacent fractures of the same orientation (see fractures 10 and 11). (5) The widths of most en échelon cracks are larger than the steps. There are, however, a few exceptions (fractures 1 and 11). (6) A rough relationship exists between length and other parameters of en échelon cracks. The normalized standard error of the linear graph generated by the correlation between length and step (Fig. 9) is ± 0.74. The error is reduced to ± 0.46 for the linear dependence between width w and length l, which suggests the approximate relationship

$$l \cong 2.5\, w.$$

DISCUSSION

Radial plumes on en échelon crack surfaces (Fig. 6) suggest that nucleation of the cracks occurred at some distance from the tips of the planar fractures (above or below it), and that extensional propagation of the cracks was both towards and away from the planar fracture. Nucleation of a new crack at some distance from the tip of the parent fracture is a well known concept (Congleton & Petch 1967).

A plot of the azimuths of the planar fractures (Table 4) reveals joint rotation (Fig. 10a). A similar pattern, on a scale three orders of magnitude larger, was interpreted in the Appalachian Plateau to be a consequence of horizontal compression along a direction that approximated to the bisector of the joint rotation pattern (Engelder & Geiser 1980, fig. 11b). By analogy, the joint pattern of the present study probably reflects NNE–SSW compression (Fig. 10a).

The two main arrays of en échelon cracks are orientated 053 and 337°. Superposing these orientations on the joint pattern shown in Fig. 10 (a) reveals a pattern (Fig. 10b) which suggests that the development of the en échelon cracks was associated with elongation in the direction of the previous direction of compression (Fig. 10a). The implication is that the en échelon cracks are a consequence of the regional unloading of the NNE–SSW compression that resulted in extension along this direction.

It should however be added that the continuous transitions from planar joints to en échelon cracks in exposure Y leave open the possibility of there having been a gradual change in the local fracture mechanism. In this connection it is suggested that the termination of curved plumes as en échelon cracks, observed by Hodgson (1961a,b), implies a local rotation of the stress axes in two stages. An early 90° rotation occurred about the horizontal axis of the minimum principal stress when it was normal to the planar joint. This resulted in superposed local shears on the fracture front (like unsynchronized breast-stroke hand motions) manifested by plume shapes. A later approximately 20° rotation of the minimum principal stress occurred around the new axial direction of the maximum principal stress that became vertical (after the above 90° rotation from the horizontal position). This resulted in the development of en échelon cracks at about 20° to the planar joint.

Shainin (1950), who characterized a system of en échelon tension fractures in a Lower Ordovician limestone at Riverton, Virginia, stated that the en échelon cracks were oriented in two conjugate arrays resulting from compression along a direction that bisected the acute angle between the arrays (Fig. 10c).

The rotation of the joints (Fig. 10a) gives rise to an approximately triangular pattern of about 1 km areal dimensions. The abundance of en échelon cracks within this triangular block and their rarity outside it seems to be significant. Additional measurements in the syncline of the present study area may reveal if the tectonic processes involved other such isolated blocks.

SUMMARY

Planar vertical joints and straight en échelon cracks are closely associated in an erosional exposure of folded Middle Eocene chalks along a 950 m strip in Wadi Naim about 9 km south of Beer Sheva. In separate outcrops X and Y, dominant joint sets are oriented 357° (N3°W) and 031° (N31°E), respectively. Each set is associated with an en échelon crack array oriented 337° (for X) and 053° (for Y).

There are five chalk platforms between outcrops X and Y, and a gradual clockwise rotation of joint orientations is apparent between the exposures. Additionally, in several exposures there are indications that the associated en échelon cracks rotate in harmony with the joints. These mutual rotations imply a model of joint development related to horizontal NNE–SSW compression. The en échelon cracks resulted from the unloading of this compression. The pattern of joint rotation suggests local tectonism within the Beer Sheva syncline involving blocks of about 1 km size.

The planar joints and en échelon cracks are straight and do not show any indications of lateral offset. Delicate, straight plumose markings characterize the surfaces of the joints, and radial plumes occur on the surfaces of some large en échelon cracks. These markings suggest that both joints and en échelon cracks are dilatant fractures. Nucleation of en échelon cracks occurred at some distance from joint tips, and their propagation was vertically towards and away from the edge of a joint. Generally, joints in outcrop X exert only limited influence on orientation and size parameters of associated en échelon cracks.

A few distorted en échelon cracks of sets at high angles to each other are associated with the straight en échelon cracks. Distorted cracks appear to be younger cracks that were partly sheared. This is a minor effect in the investigated area.

Generally, all en échelon cracks associated with a particular joint are of approximately the same orientation as each other even if the joint undulates along its strike. En échelon cracks are developed both above and below planar joints in outcrop X but occur only below planar joints in outcrop Y. At outcrop X and Y most

observations suggest discontinuous and sequential transitions from planar joints to en échelon cracks, but in exposure *Y* there are also some continuous transitions.

A linear graph which correlates widths, *w*, of en échelon cracks with their lengths, *l*, suggests the approximate relationship $l = 2.5\ w$. The normalized standard error for this curve is ± 0.46.

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