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Single-layer burial joints vs single-layer uplift joints in Eocene chalk from the Beer Sheva syncline in Israel

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Abstract

The single-layer (s.l.) joints that occur in the Lower Eocene chalks near Beer Sheva, Israel, developed during the burial history of the rock, whereas the s.l. joints in adjacent Middle Eocene chalks developed during the uplift stage. Characteristically, s.l. burial joints occur in orthogonal cross-fold and strike sets, and as conjugate sets. They precede normal faults and multi-layer joints, and they do not exhibit strike rotation, en échelon segmentation or fracture interaction with each other. These joints are generally closed, and during subsidence older beds fracture first. On the other hand, s.l. uplift joints do not occur in orthogonal or conjugate sets. They are post strike-slip faulting, contemporaneous with multi-layer joints, and exhibit strike rotation, en échelon segmentation and often interact with each other. They are occasionally opened up to several millimetres, and during uplift younger beds fracture first.

1. Introduction

1.1. Joint classification

Single-layer (s.l.) joints are abundant and they are often ascribed to burial histories (Bahat, 1991). However, s.l. joints may also form during uplift, and differentiating these two origins offers significant potential for addressing more general problems of timing in structurally complex areas. "Classification and nomenclature are the bricks and mortar of scientific thought" (Price and Cosgrove, 1990, p. 48). Therefore, investigators have classified joints according to two criteria, geometry and genetics. The classification based on geometry involves associations of joints with other structures (especially folds and faults), making it possible to divide systematic joints into sets and to estimate stress directions (e.g. Hodgson, 1961; Price, 1966; Stearns, 1968; Engelder and Geiser, 1980). Also, the determination of relative ages of joints (e.g. Bankwitz, 1966) is based on joint architecture (Hancock, 1985). In addition, the regional relative frequency of fracture classes gives a clue to the source of deformation (Bevan and Hancock, 1986). Hence, joint classification based on geometric criteria has been very useful for many years.

The ever existing need for genetic classification of joints in sedimentary rocks promoted additional propositions. Kendall and Briggs (1933) and Hodgson (1961) discussed joints that were formed early in the history of sediments. Price (1959) advanced the idea that joints were created during uplift. Price (1974) and Voight and St. Pierre (1974) pioneered the distinction between processes leading to burial and uplift joints. Engelder (1985) offered a general scheme of joint classification in clastic rocks from the Devonian sedimentary basins in the Appalachian Plateau, USA. His scheme consists of four categories: tectonic, hydraulic, unloading and release joint types. Price and Cosgrove (1990) consider fracture developments (in all rocks) related to three main geological processes, which are: 1. deformations resulting from orogenic processes, 2. deformations resulting from epeirogenic processes, and 3. 'shrinkage' caused by cooling or desiccation. Bahat (1991) proposed a joint classification scheme for the Senonian and Eocene chalks of southern Israel that includes burial, syntectonic, uplift and post-uplift groups (see further references, e.g. Bischoff, 1992; Engelder et al., 1993; Ghosh, 1993; Bankwitz and

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Bankwitz, 1994, 1997). Classifications differ in their criteria for the discrimination of the various classes within the division. The usefulness of any joint classification depends on how well specific criteria match particular field observations.

1.2. Objectives of this paper

Burial single-layer (s.l.) joints form early in the history of the rock, typically arrest at layer boundaries and are often limited to one bed. Uplift multi-layer (m.l.) joints, on the other hand, develop late in the history of the rock and cut many layers (Bahat, 1991). The discrimination between these two groups is relatively simple, because the m.l. joints, cutting many beds, have wider openings and irregular spacings which are considerably larger than those of the s.l. joints (Bahat, 1991; Ghosh, 1993, p. 492). Much more difficult is the distinction between burial s.l. joints and uplift s.l. joints, because very often they display similar outcrop features. It will be shown in this investigation that the s.l. joints from two adjacent formations in the Beer Sheva syncline differ considerably in certain properties, and these may be assigned to distinctions between burial and uplift geological processes.

2. Jointing in the Beer Sheva syncline

2.1. Background

The Beer Sheva syncline is an asymmetric fault–fold sag basin, which is part of the Syrian Arc (Krenkel, 1924), an S-shaped fold system that stretches from Syria in the north, through Israel in the centre, to Egypt in the south. It is about 1000 km long and was developed along the margins of the Arabian Plate (Fig. 1). This study concerns jointing in two chalk formations in this syncline. The Lower (or Early) Eocene represented by the Mor (or Adulam) Formation consists of thin chalk beds, 40–90 cm thick which alternate with beds of chert nodules up to 10 cm thick. The Middle Eocene, represented by the Horsha (or Maresha) Formation, consists of chalk beds without chert layers (Fig. 2). The thickness of each formation is about 100 m. Outcrops of the Lower Eocene occur

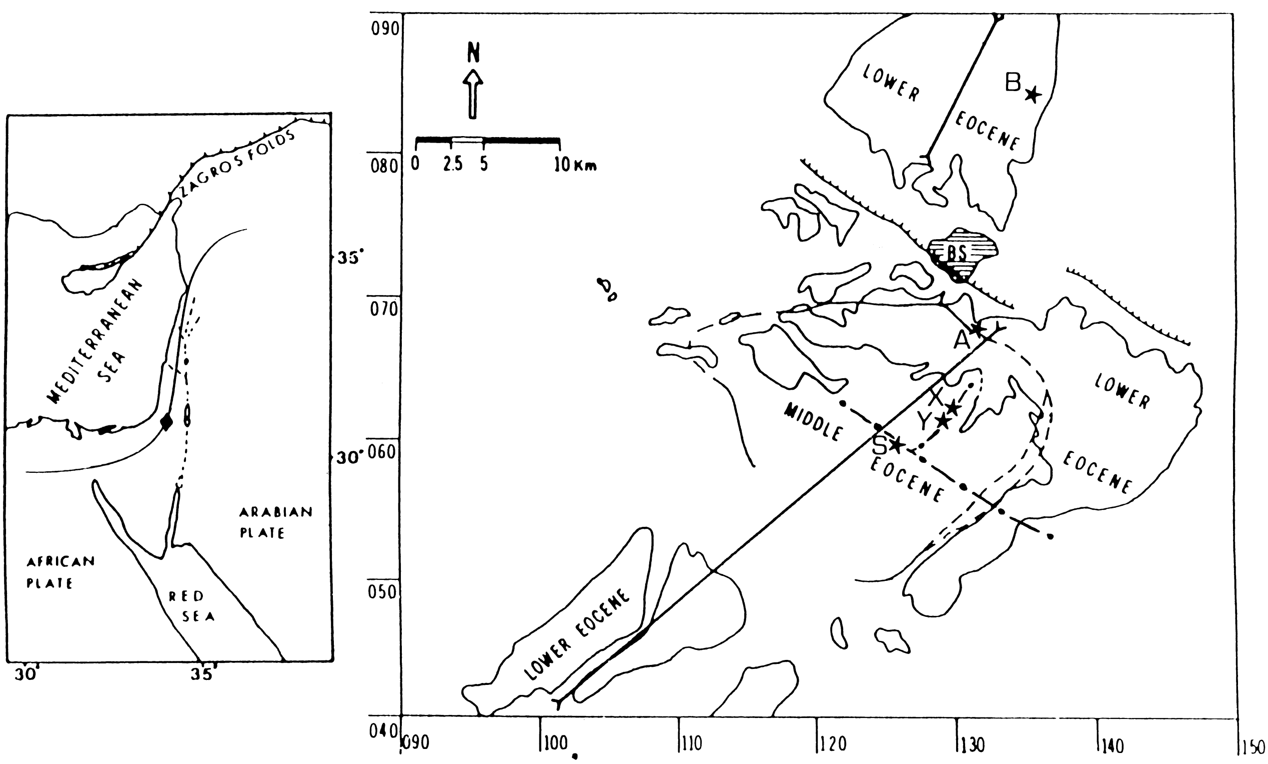

Fig. 1. Location map at left. The S curve represents the Syrian Arc and the rhomb shows the investigated area. Area map on the right, showing Beer Sheva (BS) at the centre, between the southern tip of the Shephela syncline in the north and the northern edge of the Beer Sheva syncline in the south. Straight heavy lines are portions of synclinal axes, curved heavy lines are boundaries of exposed Lower Eocene rocks (Mor Formation) after Bentor et al. (1970) and partly dashed lines are boundaries between the Lower and Middle Eocene (Horsha Formation). Barbed lines are inferred faults south of Beer Sheva after Gvirtzman (1969). Representative outcrops for the Lower Eocene are marked A and B. Representative outcrops of the Middle Eocene occur in Wadi Naim between X and Y, and at S in Wadi Secher where wadi traces are approximated by alternating lines and dots.

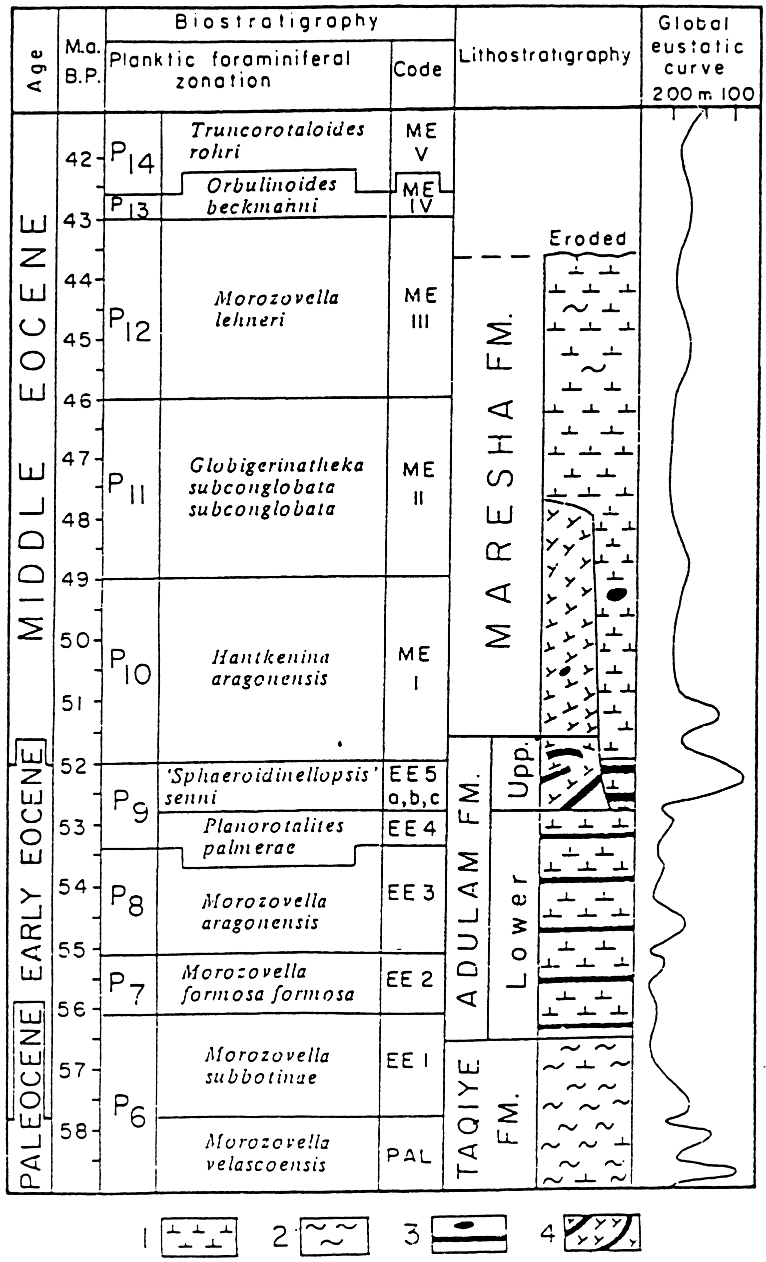

Fig. 2. Lithostratigraphy, biostratigraphy, time scale and eustatic sea-level curve of the early to Middle Eocene with reference to the Shefela area. Patterns: 1, chalk; 2, marl; 3, chert beds or nodules; 4, mass-transported units of chalk and chert (from Buchbinder et al., 1988).

in the peripheries of the syncline and the Middle Eocene is exposed in the centre of the fold (Fig. 1). These formations are only slightly folded, and joints are vertical. The regional pattern of joint orientation differs significantly in the Lower Eocene from that in the Middle Eocene (Fig. 3). Two major groups represent cross-fold joints (which occur perpendicular and sub-perpendicular to the fold axis) and strike joints (which occur parallel and sub-parallel to the fold axis) in the Lower Eocene. On the other hand, a large group which may be divided into sub-groups that have strike rotation relationships characterize the Middle Eocene (Bahat, 1986; Bahat and Grossmann, 1988).

2.1.1. The Lower Eocene

The cross-fold s.l. joints of set 328° in the Mor Formation arrest at the boundary of the chalk beds with chert beds. A normal fault that displaces these joints contains in its fracture zone fragments of chert that had been broken during early offsets of the fault, and unfractured nodules that precipitated after the cessation of fault activities (Fig. 1, station A, equivalent

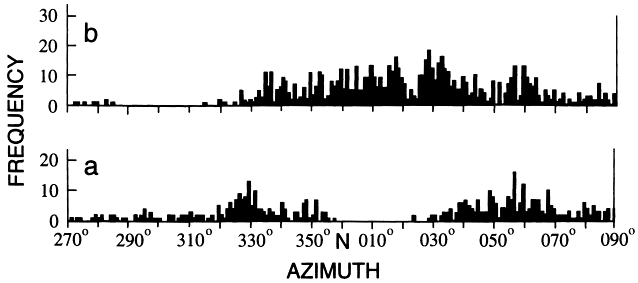

Fig. 3. Strike orientation histograms of s.l. joints from some 50 stations in the Beer Sheva syncline. (a) Mor Formation, (b) Horsha Formation (after Bahat and Grossmann, 1988).

to station 20 by Bahat and Grossmann, 1988). The precipitation of chert is associated with the diagenetic stage of the chalk (Knauth and Lowe, 1978). The burial phase is the historical stage that includes sedimentation, down-warping and diagenesis, all preceding the phases of syntectonic deformation and uplift. Chert does not occur in the overlying Middle Eocene (Horsha Formation). Therefore, both the cross-fold joints and the normal fault occurred before the sedimentation of the Middle Eocene. Hence, they were formed during the burial stage by a process controlled by the tectonic regime that prevailed in the Lower Eocene (Gross et al., 1997).

2.1.2. The Middle Eocene

In the Horsha Formation joints cut the chalk beds and terminate at the bed boundaries. Fracture markings (horizontal plumes) indicate independent fracture propagation in adjacent layers, hence they were termed s.l. joints. These fractures occur in abundance along Wadi Naim (Fig. 1, stations X to Y). Previous studies have not been conclusive about the classification of the s.l. joints cutting this formation. Although there is a general similarity in field appearance between the s.l. joints of both the Mor and Horsha Formations, set 028° cutting the latter shows indications of 'delayed fracture' (Bahat, 1987a). Delayed fracture is the term used for jointing that had not matured in the rock during its early history, and occurred at a more advanced stage (see below).

2.2. Comparison of properties of s.l. burial joints with those of s.l. uplift joints

Nine diagnostic fracture properties of single-layer burial joints and uplift joints in the Mor and Horsha Formations are summarized and compared in Table 1. These properties are further elaborated below.

2.2.1. Joint orthogonality

The Beer Sheva syncline is approximated here to behave as a quasi-basin, following Price's model (Price, 1974). The orthogonality of s.l. joints of sets 328° and 059° that developed during the burial stage is often manifested in a structure of rectangular blocks (Fig. 4a, see also, Bahat, 1989, 1991). According to Price's model uplift joints can also be expected to display an orthogonal relationship (Price and Cosgrove, 1990, fig. 9.27). However, the Horsha Formation is cut by predominantly s.l. NE-trending joints (Fig. 4b). These joints range in azimuth from 357° to 034° along Wadi Naim (Fig. 4c) and are oriented at various acute angles with respect to the synclinal axis that trends 050°, but there are almost no cross-fold orthogonal counterpart sets. Hence, joint orthogonality rarely occurs in the Horsha Formation (Bahat and Grossmann, 1988).

2.2.2. Conjugate joints

Conjugate hybrid joint sets (Hancock and Al-Kadhi, 1978; Hancock, 1985) are present in the Mor Formation (Fig. 4d) and do not occur in the Horsha Formation (Bahat, 1987b; Bahat and Grossmann, 1988). The geometry of these conjugate joints corresponds to the general scheme of jointing by lateral compression normal to the fold axis (e.g. Price, 1966, fig. 43a, sets ac, S' and S''; Stearns, 1968, fig. 10, set 1,

Table 1
Fracture properties of single-layer burial and single-layer uplift joints

Single-layer burial joints (Mor Formation)	Single-layer uplift joints (Horsha Formation)
1. Orthogonal cross-fold and strike sets	There is no orthogonal jointing
2. There are conjugate joint sets	There are no conjugate joint sets
3. Joints generally are pre early normal faulting	Joints are post early strike-slip faulting
4. Not contemporaneous with any m.l. set	Contemporaneous with the m.l. set 062°
5. There is no joint rotation	Joint rotation is extensive
6. Older beds fracture first	Younger beds fracture first
7. No fracture interaction among joints	Considerable fracture interaction among joints of set 028°
8. No en échelon segmentation	Fringes of en échelon segmentation associated with NE-trending joints
9. Closed joints (aperture < 0.1 mm)	Joint opening varies considerably (from 0 to > 10 mm)

Sources for data and explanation are given in text.

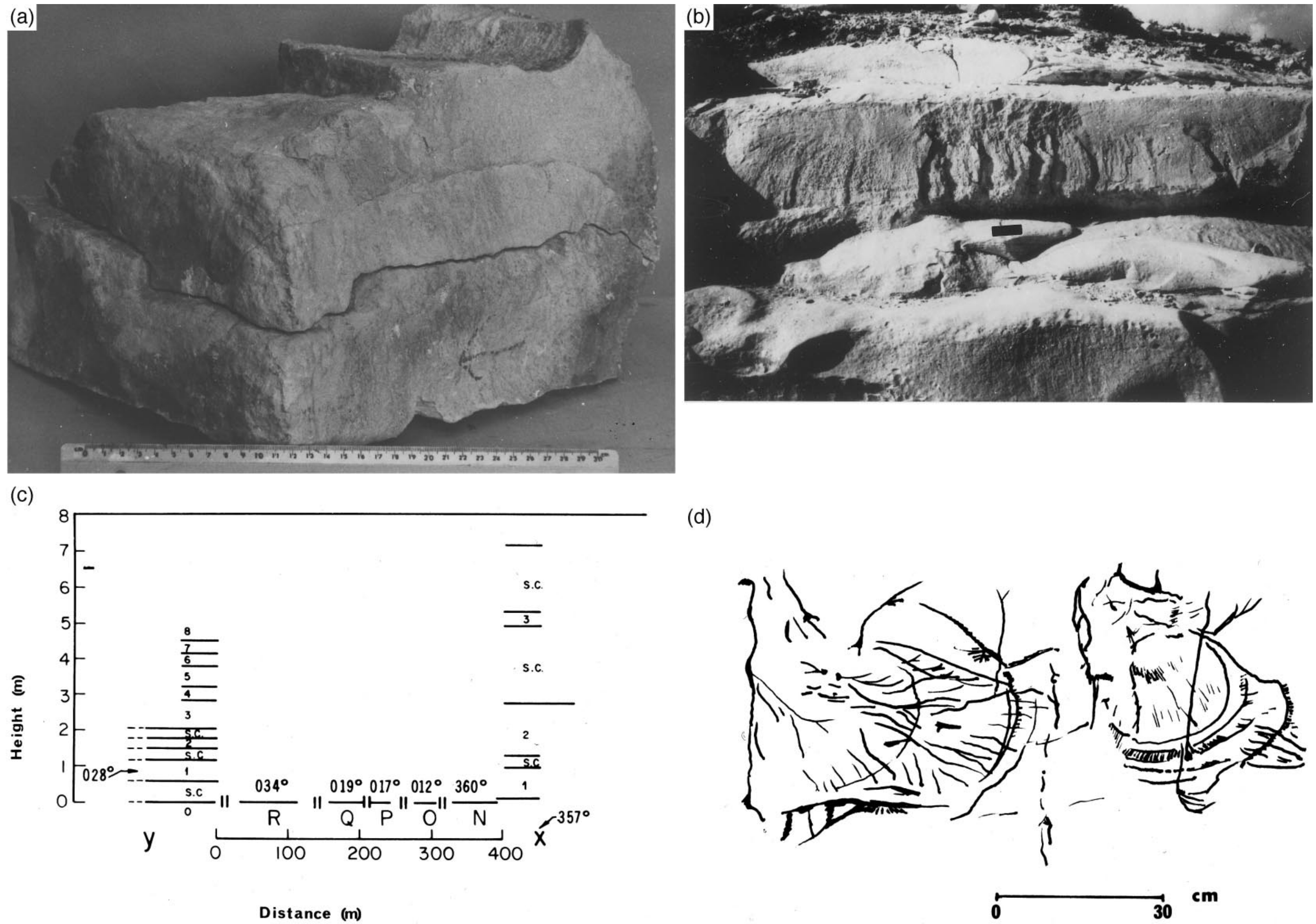

Fig. 4. (a) Rectangular block formed by orthogonal joints cutting the Mor Formation in station A in Fig. 1. The two parts of the block are intact along the hair-line joint (scale is 30 cm). (b) A single-layer NE-trending joint from the Horsha Formation in outcrop Y (see c). The upper part of the parent joint arrests at layer boundary. The lower part consists of a set of en échelon segments. Scale bar is 20 cm. (c) Outcrops X and Y including floors N to R between them along Wadi Naim, 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. (d) Drawing of two conjugate hybrid joint sets that occur in a single outcrop from the Mor Formation (station A). The undulation marking the joint on the right is oriented 328° and the plume marking on the joint on the left is oriented 342° (from Bahat, 1991).

fractures E and S) during the early history of the fold (Burger and Hamil, 1976). This closely resembles early fracture in the Beer Sheva syncline, as manifested by the burial s.l. joints that developed in the Mor Formation during the Lower Eocene.

2.2.3. Delayed fracture of the s.l. joint set 028°

Joint set 028° represents the s.l. NE-trending joints in the Horsha Formation (Bahat, 1987a). Set 028° occurs with a pronounced azimuth uniformity in layers 1 and 2 along Wadi Naim (Fig. 4c), as indicated by a mean of 028° with a standard deviation of $\pm 2°$ (based on 47 measurements, Bahat, 1987a). In layer 1 joints of set 028° occur near a fault termination zone consisting of three major elements (Fig. 5a and b): (a) a primary fault, (b) secondary faults, and (c) a joint set associated with the faults.

(a) The primary fault is a vertical right-lateral strike-slip fault, striking 318° (Bahat, 1987a).

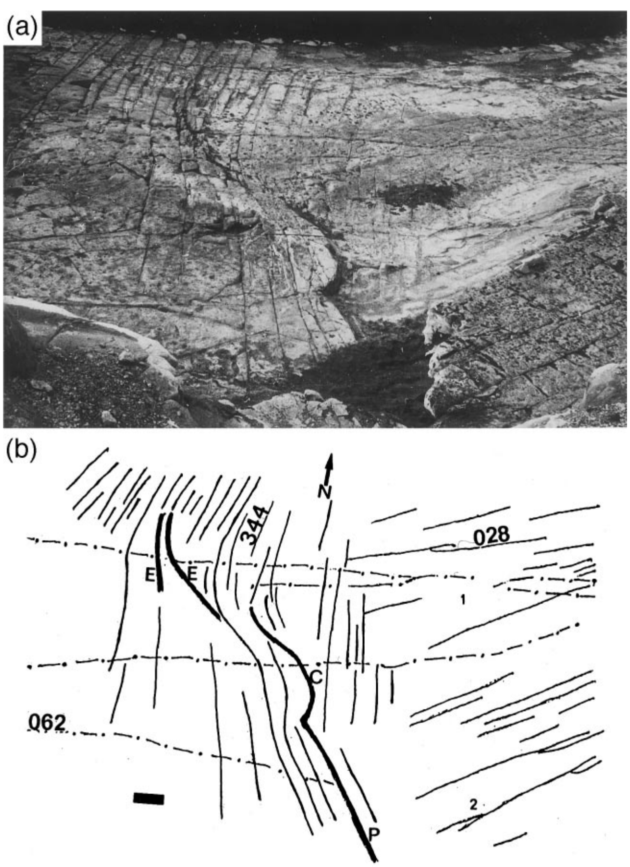

Fig. 5. General view of the fault termination zone in the centre of photograph (a) and drawing (b). The primary fault P and the three secondary faults—the curved C and two left-stepping en échelons marked as E, are shown by thick lines. The joints of sets 344° and 028° are marked by thin lines and set 062° is inscribed by alternating lines and dots. Exposures of layers 1 and 2 are shown by respective numbers. The photograph is taken from the cliff above P and therefore is somewhat optically distorted. Scale bar is 1.5 m.

(b) A set of three partly curved secondary faults (Chinnery, 1966) initiate at the tip of the primary fault.

(c) A joint set striking 344° is confined to a zone (some 7 m wide) on both sides of the fault in the same layer, and does not occur elsewhere in the outcrop. The joints curve in conformity with the primary and secondary faults.

Therefore, the joints of set 344° are considered to be genetically associated with the faults, and they are termed syntectonic joints (Bahat, 1991, fig. 5.13). Three observations imply that set 344° predates set 028°. First, joints of set 028° approach the area influenced by the fault in layer 1 and arrest at its periphery (they terminate at the western side of Fig. 5). Second, a left lateral offset of 1 cm in set 344°, along set 062° (see below) is observed in one location, but adjacent 028° joints are not displaced (they are too small to be shown in Fig. 5). Third, secondary cracking of set 028° that 'hook' in sub-parallel and sub-perpendicular directions to previous free surfaces of set 344° are common (Bahat, 1987a). Hence, joint set 028° postdates three structures in the same chalk layer (Fig. 5). This sequence demonstrates a 'delayed fracture' of set 028°. The fracture succession in the Horsha Formation differs from the joint vs fault age relation in the Mor Formation, where joint sets 328° and 059° (particularly the former) preceded normal faults that were associated with the burial stage during the Lower Eocene (Bahat, 1991).

Delayed s.l. jointing in the thin, stratigraphically young layers of the Horsha Formation (set 028°, Bahat, 1987a) probably resulted from lack of sufficient overburden to exert the necessary pore pressure for creating joints during the burial stage. There are no sediments younger than Middle Eocene in the investigated area (Bahat, 1989). Although there is evidence for Upper Eocene–Oligocene sediments (The Bet Guvrin Formation) along the coastal plain further west (Buchbinder and Zilberman, 1997), these were not exposed near Beer Sheva, possibly due to uplift and denudation in the Late Eocene (Benjamini, 1984).

2.2.4. Joint contemporanity

Set 062° shows characteristics of multi-layer joints in the Horsha Formation. Fractures of this set occur along various parts of Wadi Naim and may be tens or hundreds of metres long (Bahat, 1991, p. 277). These fractures are irregularly undulated, forming anastomosing patterns along the strike (Bahat, 1987a). There are indications of contemporanity of sets 028° and 062° because joints of these sets terminate at contact with one another (Fig. 6a and b). Set 062° is a syntectonic one and it signifies the stage of the relaxed pressure perpendicular to the synclinal axis which led to

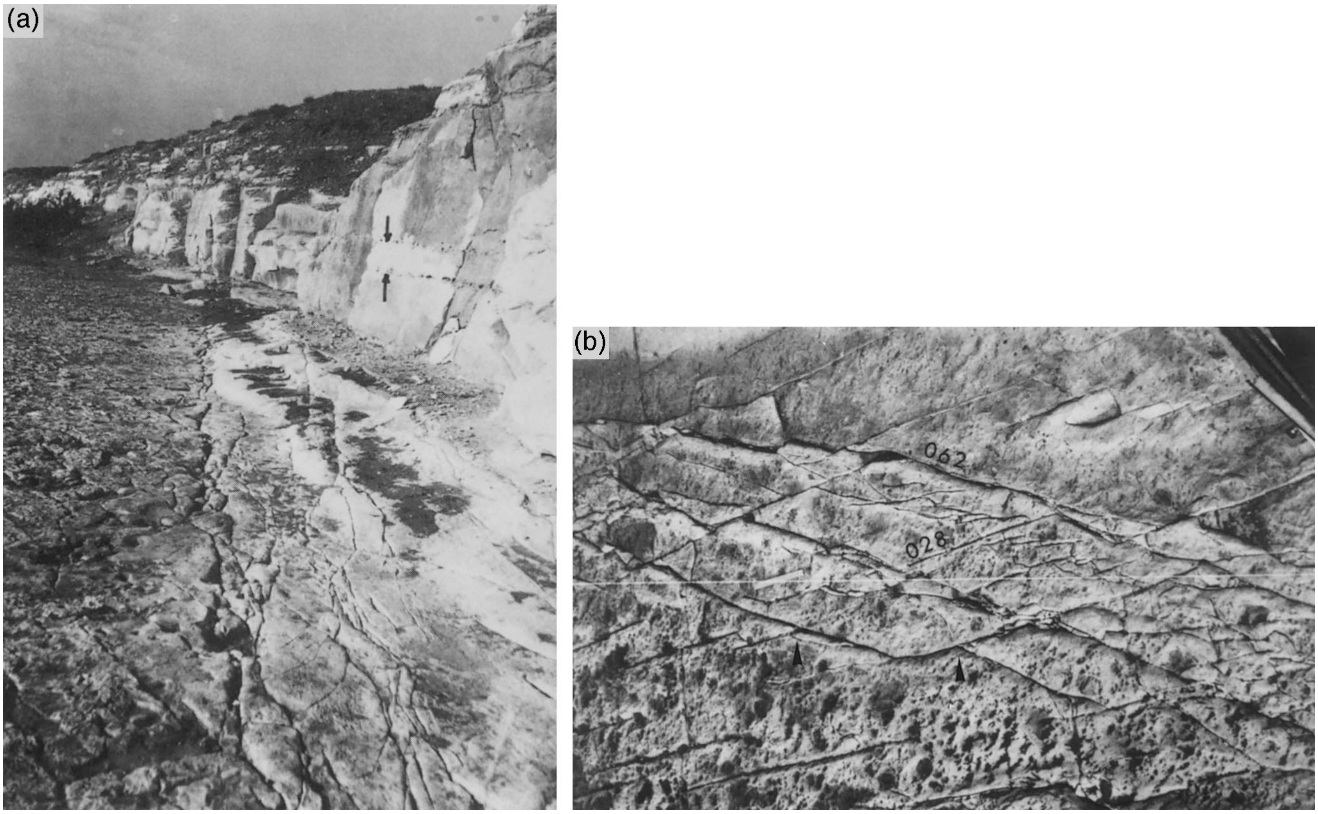

Fig. 6. (a) Chalk stratification and jointing in Middle Eocene chalks at Wadi Naim. Anastomose fractures of set 062° (at centre of picture) cut through layers 1 and 2, and continue into the cliff. Note the irregularity in the floor and straightness of these fractures in the cliff. Arrows mark the thickness of layer 5 (60 cm) at the cliff. (b) Interaction between joints of sets 028° (sub-parallel to the 30 cm scale at left-centre) and 062° in chalk of the Horsha Formation (outcrop Y). Joints of both sets arrest at each other (at arrows), suggesting contemporanity.

buckling-rebound of the syncline (Bahat, 1987a). The contemporanity of sets 028° and 062° suggests that the formation of the former set was also associated with the buckling-rebound of the syncline.

2.2.5. Rotation of joint strikes

There is a prevalent pattern of joint rotation of the NE-trending joints in the Horsha Formation (Fig. 4c, also Bahat, 1986, 1997) but not in the Mor Formation. Seven outcrops of rock floors alternate along 700 m at the wadi level with patches of talus between exposures X and Y (Fig. 4c). 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. Strike measurements show that, with the exception of floor R, there is a gradual clockwise rotation of joint orientation between outcrops X and Y (Bahat, 1986).

The rotation of s.l. joints during uplift in this formation is proposed to have been activated by the evolution of different stress fields in the Beer Sheva syncline during two stages (Fig. 7a–c):

(a) Maximum horizontal stress S_H paralleled the short axis x of the syncline and the minimum horizontal stress S_h paralleled the long axis y (Fig. 7a) during buckling-folding, before uplifting has begun (Picard, 1943; de Sitter, 1962).

(b) Buckling-rebound occurred when the compression along x relaxed and became S_h and the compression along y became S_H (Fig. 7b). This was associated with the initiation of uplift (Bahat, 1987a).

The gradual transition from stage a to stage b was associated with the rotation of the horizontal stresses (Fig. 7c) that matche actual rotation of joint strikes along Wadi Naim (Bahat, 1986, figs. 2 and 10a, b). More specifically, at an early stage of rotation (Fig. 7c) the direction of S_H was coaxial with the joint set 344°, and this S_H activated a strike-slip fault (Fig. 5) that was oriented 318° (Bahat, 1991, p. 275, also study in preparation). Further rotation occurred from 344° to 062° through the range 012°–034°, involving the formation of set 028° (as mentioned above) (Fig. 4c, Bahat, 1986, 1987a). Above floors 1 and 2 in outcrop Y there are northeast oriented joints that cut layers 4–8 in the cliff (Fig. 4c). The mean of 24 joints from a set cutting layer 5 is 035° ± 8° (Bahat, 1987a). Joints of set 062° show distinct morphologies when they cut

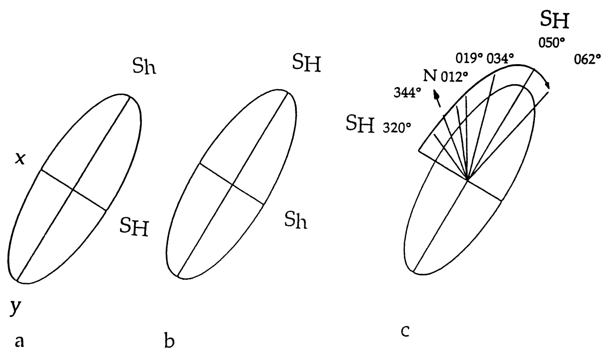

Fig. 7. Model of the evolution of the Beer Sheva syncline under different stress fields, during two stages. (a) During buckling, maximum horizontal stress S_H parallels the short axis x of the syncline and the minimum horizontal stress S_h parallels the long axis y. (b) Buckling-rebound occurred when the compression along x relaxed and became S_h and the compression along y became S_H. (c) Clockwise rotation of the horizontal stresses during the transition from a to b.

floors 1 and 2, compared to their appearance in layers 4–8. They cut layers 1 and 2 in anastomosing patterns and overprint set 035° in the cliff while maintaining strict planar shapes (Fig. 6a). This difference reflects different tectonic conditions (Bahat, 1991). In summarizing the fracture-contact relationships one notes that talus patches between exposures (Fig. 4c) may obscure some joint abuttings, but several relative timings are clear. Set 344° is the oldest, late fractures of set 062° are the youngest, and set 035° in layer 5 is younger than set 028° in layers 1 and 2. These provide reasonable evidence for a clockwise stress rotation from azimuth 344° to azimuth 062° (Fig. 7c). A current study (unpublished report by Bahat and Shavit, 1997) shows a similar joint rotation in Middle Eocene layers along Wadi Secher which runs about normal to the synclinal axis.

2.2.6. Fracture initiation in younger layers

The joints oriented 012°, 017° occur in upper layers further upstream along Wadi Naim, compared to joints oriented 028°, 034° which are exposed downstream (Bahat, 1986). Since the layers are approximately horizontal, the joints oriented 012° occur in younger layers. Accordingly, a clockwise rotation of S_H from 344° to 062° (Fig. 7c) should require jointing initiation of sets 012° and 017° in upper layers before fracture of sets 028° and 034° in deeper layers. This sequence is consistent with the general downward propagation of uplift joints (Bahat, 1991, p. 293). During uplift the stress gradient is such that the least principal stress decreases downward, causing the greatest strain at the surface. Consequently, both single-layer and multi-layer joints start to form in the younger layers advancing downward. The above succession is opposite to the one associated with burial joints, where jointing commences in deeper (older) layers which are the ones that mature earlier for fracture (Hodgson, 1961).

2.2.7. Fracture interaction

There is no fracture interaction between joints cutting the Mor Formation. On the other hand, there is an intense interaction among non-coplanar joints of set 028°, whereby adjacent joints curve towards each other in various styles (Bahat, 1987a). A detailed study of this and related joint interactions in different chalk formations strongly suggests that jointing in the Mor Formation occurred under greater differential stresses than those leading to fracture of the 028° set (Bahat, 1991, p. 317). This corresponds to the general pattern of increase in the differential stresses during subsidence and its decrease when uplifting occurs (Engelder, 1985). Hence, fracture interaction in set 028° was associated with a decrease in differential stresses during an uplift process.

2.2.8. Dilatant en échelon fringes

The above property suggests that set 028° developed under reduced stresses corresponds to the exclusive occurrence of en échelon fringes along the NE-oriented joints (Fig. 4b, also Bahat, 1986), and implies fracture under limited overburden pressures (Bahat, 1991, 1997). There is no en échelon segmentation in the s.l. joints cutting the Mor Formation, possibly because they fractured under greater effective stresses.

2.2.9. Joint apertures

Burial s.l. joints of a given set in the Lower Eocene generally display a uniform orientation and spacing, and aperture which is often quite small (<0.1 mm) (Fig. 8a and b and Bahat, 1991, p. 257). Fig. 8(a) shows three layers of chalk alternating with chert beds. The joints cutting the third layer from the bottom (at the upper part of the 90 cm scale) are s.l. cross-fold joints that reveal uniform fracture properties. The layer at the lower part of the scale is cut by s.l. strike joints whose orientation does not disclose the uniform properties at this angle. Fig. 8(b) displays many cross-fold s.l. joints maintaining the same small aperture and a multi-layer joint that cuts the entire outcrop at a later stage and has a much greater opening (>10 mm). On the other hand fracture properties may vary considerably in the Middle Eocene, particularly apertures of s.l. joints of a given set (Fig. 8c and d).

The closed s.l. joints in the Mor Formation vs the occasional open joints in the Horsha Formation support the suggestion that, whereas the former joints reflect overall compressional conditions, the latter imply conditions of released stresses during uplift.

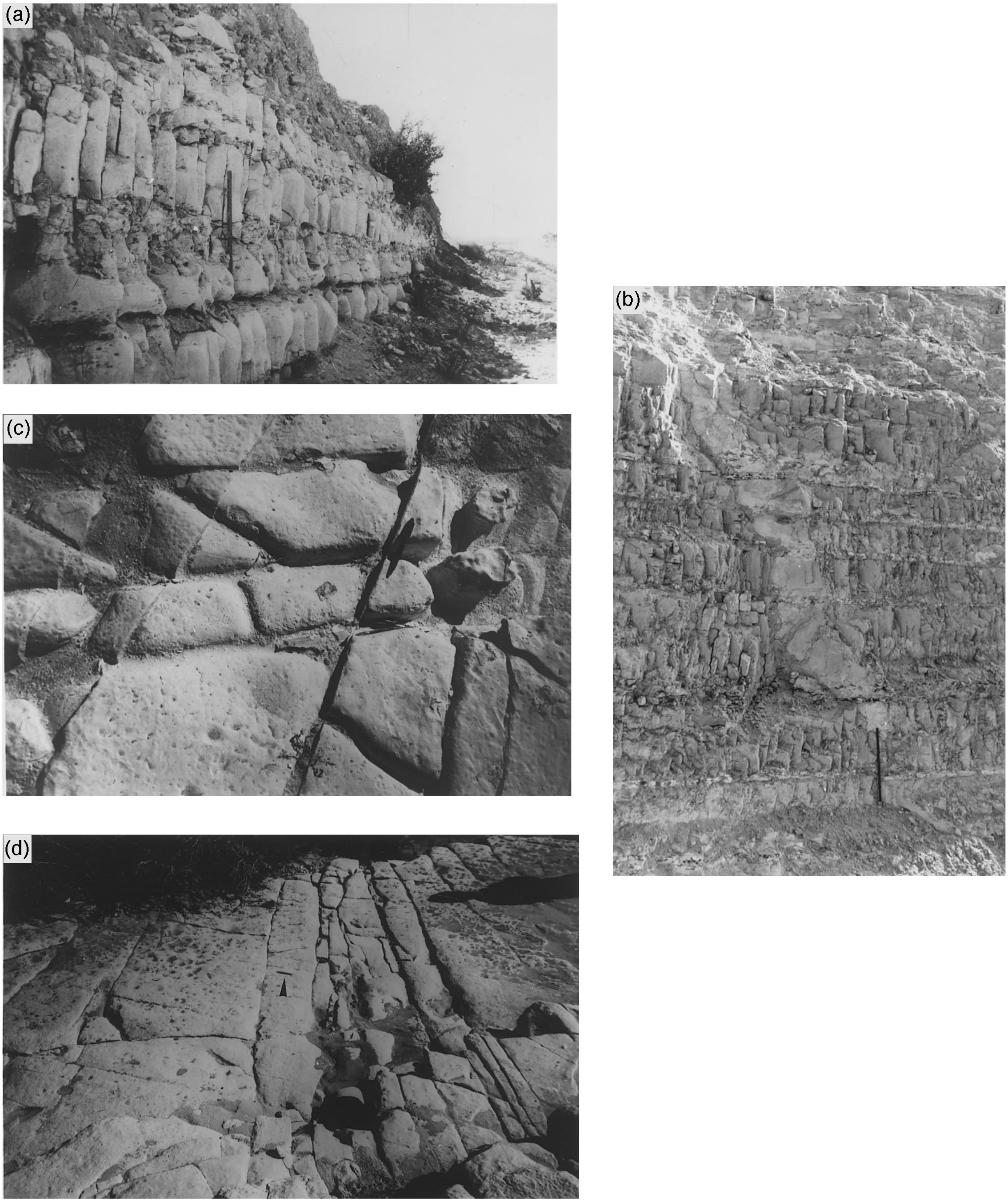

Fig. 8. (a–b) Single-layer joints from the Mor Formation (scales are 90 cm) showing uniform apertures ($\leq$0.1 mm). (a) Joints in four chalk layers (Fig. 1, outcrop A), and (b) joints in many layers are compared with a multi-layer joint that has a greater opening (> 10 mm) (Fig. 1, outcrop B). (c) Four s.l. joint sets cutting the Horsha Formation showing considerable variability in spacing and opening. Particularly, in the set that parallels the pen, the left joint is incipient whereas the right fracture is widely open (several mm) (c and d are from outcrop S in Wadi Secher, Fig. 1). (d) Non-uniform spacing and apertures in joints of a given set (note arrowed black pen in the centre of figure for scale).

3. Conclusions

Single-layer joints are abundant and they are often ascribed to burial histories. However, s.l. joints may also form during uplift. Differentiating these two origins offers significant potential for addressing more general problems of timing in structurally complex areas.

Whereas s.l. burial joints that comply with quasi-basin fracture conditions (Price, 1974) often form orthogonal sets, s.l. uplift joints in the Beer Sheva syncline manifest local stress changes by strike rotation.

Strike rotation in s.l. uplift joints does not go hand in hand with conjugate sets.

Suppression of s.l. jointing during the burial and syntectonic stages is a prerequisite condition for delayed fracture, leading to s.l. uplift jointing.

Accordingly, various combinations of contemporaneous s.l. and m.l. fractures can be expected during uplift, including joints postdating syntectonic faults.

During uplift the stress gradient is such that the least principal stress decreases downward causing the greatest strain at the surface. Consequently, both s.l. and m.l. joints start to form in the younger layers advancing downward.

This stress gradient is associated with a decrease in differential stresses and commensurate increase in fracture interaction of joints and en échelon segmentation in joint fringes. It promotes opening of s.l. uplift joints, compared to s.l. burial joints that generally are closed.

These observations need to be further verified in other fracture provinces consisting of similar lithologies and structures.

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