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Dedicated to Prof. Dr. Bankwitz on
the occasion of his 80th anniversary

Comparative tectonofractography: fracturing in 19 jointing provinces, experimental results, fracture mechanics considerations and province classification

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Abstract: This study presents a comprehensive synthesis of tensile fracturing phenomena from 19 provinces that display jointing in four continents, incorporating experimental results and fracture mechanic considerations. Three data assemblages are set in three tables (Tables 2–4) and provide the basis for the analysis. A series of new associations of various joint attributes emerges. They connect the joint type (single layer versus multilayer fracturing), the joint class (tectonic formation conditions) and joint relationship (joint orthogonality, the ladder pattern versus the grid pattern and joint rotation). These are further linked to lithology, fractography, joint propagation velocities and horizontal versus vertical propagation constraints. While arrest marks conspicuously occur on certain sandstones, plumes exclusively decorate particular igneous rocks. Tensile failure in glasses, ceramics, blasted rocks and in naturally fractured granitoids, as well as rarely in limestone, display two common features: smooth mirror planes that practically lack arrest marks and only rarely plumes imprinted on them, while their fringes are decorated by hackles. These are fractographic features that indicate unstable fracturing. Finally, a classification of jointing provinces is contemplated (Table 5).

Kurzfassung: Die Studie repräsentiert eine vergleichende Synthese von Zugbruch-Phänomenen aus 19 Provinzen, welche Klüftung in vier Kontinenten widerspiegeln. Drei Datensätze, aufgelistet in drei Tabellen (Tab. 2–4) bieten die Grundlage für die Analyse. Eine Serie neuer Assoziationen von verschiedenartigen Klufteigenschaften wird deutlich. Sie verknüpfen Klufttyp (Bruch von Einzellagen im Verhältnis zum Bruch durch mehrere Schichten), Bruchklassen (tektonische Bildungsbedingungen) und Kluftbeziehungen (orthogonale Klüfte, Leiterstrukturen im Verhältnis zu Netzstrukturen und Kluftrotation). Sie zeigen auch Verbindung zu Lithologie, Fraktografie, Kluftausbreitungsgeschwindigkeit und zu horizontalen im Verhältnis zu vertikalen Ausbreitungszwängen.

Während Arrestmarken in bestimmten Sandsteinen auffallen, dekorieren Federstrukturen („plumes“) besonders magmatische Gesteine.

Zugbrüche in Glas, Keramik, gesprengten Gesteinen und in natürlich geklüfteten Granitoiden, so wie auch selten in Kalkgestein, weisen zwei verbreitete Merkmale auf: (1) glatte Spiegelflächen („mirror planes“), auf denen Arrestmarken praktisch fehlen und selten Federstrukturen („plumes“) ausgebildet sind, während (2) ihre Randzonen („fringes“) von Randklüften („hackles“) besetzt sind. Diese fraktografischen Merkmale zeigen eine instabile Bruchbildung an. Letztendlich wurde eine Klassifizierung von Kluftprovinzen angestrebt (Tab. 5).

Keywords: jointing, fractography, experimental, fracture mechanics, propagation velocities

Schlüsselwörter: Klüftung, Fraktografie, experimentelle Untersuchungen, Bruchmechanik, Ausbreitungsgeschwindigkeit

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1. Introduction

1.1 General

Joints are the most common fracture structures in the earth crust. They are far more abundant than faults. Joints need to be extensively considered in connection with many applications in the fields of mining, hydrology, oil and gas production, civil engineering, CO_2 storage in the ground, and more. Tectonically, joints support a leading method for deriving palaeostress directions (mostly the least compressive principal stress σ_3 where $\sigma_1 > \sigma_2 > \sigma_3$), and occasionally estimation of palaeostress magnitudes.

The coupling of joint tectonics with fractography is termed tectonofractography (e.g. Bahat 1991, Hull 1999, Ramsay & Lisle 2000, Pollard & Fletcher 2008). It embraces a classification of joints cutting sedimentary rocks into four groups according to their distinct tectonic environments: burial, syntectonic, uplift and post-uplift. Post-uplift joints form after uplift joints, and their formation is typically influenced by the late physiographic conditions. With a certain modification this grouping is also applicable to igneous rocks (e.g. Engelder et al. 1993, Ghosh 1993, Bankwitz & Bankwitz 1994, 1997, Źak et al. 2006; Table 1).

In spite of these advances, there are still certain jointing mysteries, awaiting their deciphering. The present study incorporates observations on various tensile fracture surfaces in different rock assemblages from 19 jointing provinces that relate to diversified tectonic settings. Also included in this study are fractures from different technological materials. A major issue of concern is the distinction between slow, subcritical joints and rapid, post-critical joints. Certain aspects of joint orthogonality are also included in this investigation.

1.2 Fractography

The fracture surfaces of brittle materials, like rocks, inorganic glasses (and to some extent polymeric glasses), ceramics and metal alloys record the various stages of fracture propagation by some ten fractographic features (Fig. 1a). Fracture surface markings are distinguished by two divisions: First, sequentially, there is a series of early features on the mirror plane, of which the early arrest marks (or undulations) and plumes are the most common, and the late markings consisting of the en echelon cracks (or hackles), which reside on the fringe, beyond the mirror boundary. Second, the fractography is schematically divided into "slow fracture

Table 1: Joint classifications in sedimentary and granitic rocks.

Joint classification in sedimentary rocks		
1.	burial	early
2.	syntectonic	late
3.	uplift	late
4.	post-uplift	late

Joint classification in granitic rocks		
1.	cooling	early
2.	syntectonic	late
3.	uplift	late
4.	post-uplift	late

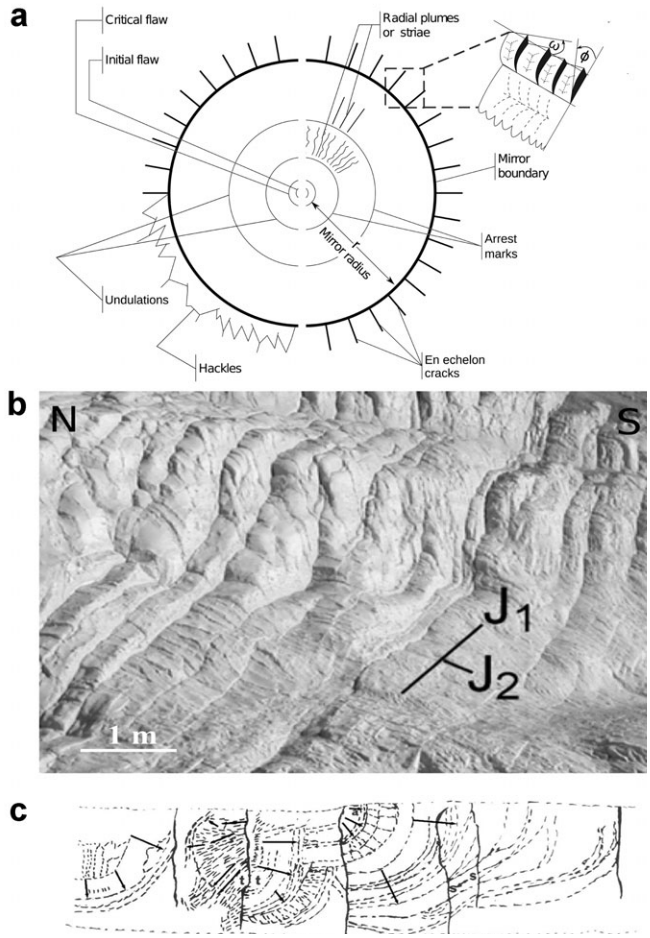

Fig. 1: (**a**) Schematic summary of the various fractographic features, which appear both on rapidly and slowly propagating fracture surfaces. The insert should be slightly rotated for showing its mirror boundary at the same orientation like in the major figure. See details in the text. (**b**) Two orthogonal sets, in which the dominant (systematic; Hodgson 1961) set J1 formed earlier and maintained relatively large spacing, and the later (non-systematic) set J2 filled the formed areas in smaller spacing, making a ladder pattern (modified after Weinberger & Bahat 2008). (**c**) Two orthogonal sets, proven fractographically that they have alternated each other in time, they form a grid pattern. The single layer set which parallels to the page has a cross fold orientation, and it consists of four joints, which are marked by fractographies and arrows that show directions of propagation. The cross fold joint on the right side was cut by the later two strike parallel joints, which are orthogonal to the page and are marked "s". However, the two cross fold joints in the middle initiated at a strike parallel joint, marked "t" at its two sides. The layer thickness is 40 cm (from Bahat 1991: Fig. 4.8).

propagation" half at right, and "rapid fracture propagation" half at left. The distinction between slow ripple marks, which are known as arrest marks, and rapid ripple marks, which are termed undulations is adapted here (Weinberger & Bahat 2008). The mirror radius is measured between the critical flaw and the mirror boundary.

In the insert at right (Fig. 1a), the tilt angle ϕ is measured along the mirror boundary between the mirror plane and the fringe plane if flat, or its tangent if curved. The twist angle ω is measured between the continuation of the mirror plane and the surface of the best-exposed segment at its end.

Some of the above fractographic features that form on the mirror plane occasionally occur also on the fringe, but these are beyond the scope of the present study.

Fractographic descriptions of plumes in geological outcrops approximate striae that often appear experimentally and not frequently in nature. Fracture mechanically both form by mixed modes I and III (e.g. Lawn & Wilshaw 1975: 67). Plumes occur as multi micro-cracks in "quasi-dendritic" styles, and are mostly connected with jointing in rocks, whereas striae appear as individual, straight shaped cracks and are often associated with fracturing in technological materials, and occasionally in rocks as well.

The terms mirror plane and parent joint are used interchangeably in this study. In granitoid rocks, where large joint surfaces are not obscured by layer boundaries, mirror planes occur in their full shape. However, in sedimentary rocks, major parts of mirror planes are very often cut by layer boundaries. In such a case, the joint surfaces become indiscernible, and the term parent joint is preferred.

It is generally accepted that joints form basically by mode I loading (Pollard & Segall 1987, Engelder et al. 1993). Specifically, fractography indicates that joints are essentially, but not entirely, products of tensile stress (Bahat 1979). Generally, the differences in actual local stresses that are imposed on joint surfaces are substantial, even under unchanged remote stresses. Commensurately, since much of the histories of most joints is sub-critical, the vast detailed variations of arrest marks and plumes, which record slow propagation on joint surfaces, are quite variable. In an attempt to decipher some of its complexity this study groups examples from 19 jointing provinces aiming at their categorisation (Tables 2–4). A joint fracture province is a region that contains a joint set or more than one set cutting a uniform lithology by a common stress history. Thus, all joint sets in a given province are genetically linked to each other.

1.3 Joint orthogonality

Generally single layer joints fall into two major categories, orthogonal (or sub-orthogonal) systems, in which the two major sets are at an angle of about 80°–90° to each other, and non-orthogonal sets. The orthogonal joint systems appear in two forms. The "ladder pattern" displays hierarchy of an early set of systematic long parallel fractures and a late set of non-systematic joints, which abut the earlier set at about 90° without crossing it, forming the H-shaped abutment (Hancock 1985; Fig. 1b). The "grid pattern" relates to non-hierarchic two sets of fractures which mutually cross-cut (Fig. 1c; Rives et al. 1994). Price (1966: 135) and Price & Cosgrov (1990: 211) suggest that mutually orthogonal sets are formed sequentially during uplift, because as soon as fracturing takes place the tensile stresses are released and the direction of the least compressive principal stress (σ_3) changes, while always remaining perpendicular to the joint. Thus, stress release results in orthogonal switch in the direction of σ_3. Rives et al. (1994) induced stress and stress relaxation by loading and unloading techniques on a brittle varnish layer bonded to a PVC plate in simulating the formation of orthogonal joint sets. They show that the "ladder pattern" forms by loading and unloading: The early joints are induced by loading and the late joints by the unloading, leading to stress relaxation. On the other hand, the formation of the "grid pattern" probably results from two separate loadings with different (orthogonal) loading directions.

2. Fractographies on joints from 19 jointing provinces

Examples of fractographies from the various fracture provinces (Tables 2–4) are presented in Figs. 2 and 3. In the tensile stress intensity K_I versus fracture velocity V plot (Fig. 4), stable fracturing occurs under sub-critical conditions, at the left side of the D-E part of the curve, while unstable fracturing occurs under post-critical conditions, at the right side of the D-E part of the curve.

2.1 Joints that formed stably

This chapter relates to two fracture types. Firstly, joints that formed between layer boundaries in sedimentary rocks (Table 2). Secondly, joints that cut thick sedimentary outcrops and certain magmatic rocks (Table 3). In the latter rocks (massive granitoid – province 6 and volcanic rocks – province 4) jointing forms between earlier sub-horizontal joints and between two close partings resembling layer boundaries.

Table 2 contains nine rock examples from eight jointing provinces. These data demonstrate the commonality of arrest marks and plume occurrences on burial and syntectonic as well as uplift joints. While some joints occur in orthogonal systems, others appear as individual sets, oriented along particular strikes or showing strike rotation. Itemisation of the various joint types from Table 2 and their fractographic associations follows.

1. Fractography was examined only on the cross fold set (sub-normal to the Ramon Anticline) that cuts flint clay under syntectonic conditions. Strike joints (striking sub-parallel to the anticline) are far less abundant. The mature joints occur in close associations with embryonic joints. While the mature joints are decorated by both, arrest marks and plumes (Fig. 2a), the embryonic joints reveal merely arrest marks that only started their propagation, and never reached advanced fracture velocities (Bahat 1991: Fig. 3.42). This dis-

tinction corresponds to recent results suggesting that plumes designate faster, more advanced propagation than arrest marks (e.g. Weinberger & Bahat 2008, Bahat et al. 2008a).

2. The Santonian chalk exhibits discrimination between plumes on cross fold joints and arrest marks on strike joints due to greater stress differentiation along the cross fold direction (under syntectonic conditions; Weinberger & Bahat 2008). Consequently the joint ladder pattern (Fig.1b) is common in these joints. This example demonstrates a case where plumes are absent on strike joints, due to slow fracture propagation.

3. Jointing under burial conditions in the Lower Eocene chalks reveals the grid pattern (Fig. 1c), and that arrest marks and plumes occur in the two orthogonal directions. However, plumes seem to occur less abundantly on strike joints than on cross fold joints. The plumes decorating these joints are coarse, i.e. the widths of barbs are from 0.5 cm to several centimetres (Bahat 1987).

4. & 5. Jointing in the Middle Eocene chalks occurred under conditions of stress release during uplift. The plumes on the parent joints of these two sets are similar and abundant. However, the orientations of these sets are entirely different, and so are their fringe patterns: While set 012°–035° is associated with a single en echelon fringe, set 350°– 014° is decorated by two en echelon fringes (above and below the parent joint; Fig. 2b). These differences indicate that the two sets represent different fracture provinces (Bahat et al. 2008b), and that they record stress fields and tectonic conditions, which were altered during their advanced propagation stages, apparently shown by their distinct fringes. The plumes decorating these joints are delicate, i.e. the widths of barbs are less than 0.5 cm (Bahat 1987).

6. The single layer syntectonic jointing is common on both sides of the Bristol Channel (West England and South Wales). For unknown reason fractography is rare on many of the parent joints that cut these limestones. Important exceptions are the plume appearances only on thin rock layers (several cm thickness; Roberts 1961), and rarely, more compounded fractographies (Belayneh 2004), all suggesting stable jointing, which is common to the two sides of the Bristol Channel.

7. Both arrest marks and plumes decorate the cross fold joints that cut the Cretaceous dolostone near Jerusalem (Weinberger 2001). No orthogonal jointing is observed in this set (Fig. 2c) (although a later joint set at a high angle occurs adjacently).

8. & 9. Sets 320°–330° and 342° by Younes & Engelder (1999) are assumed to be equivalent to sets Ib (333°) and Ia (346°), respectively, by Engelder & Geiser 1980, Bahat & Engelder (1984), Bahat (1991: Tables 5.1 and 5.2). While plumes decorate the earlier set (333°) in the siltstone, arrest marks occur on surfaces of the set which cut the shale (346°; Fig. 2d). Although the latter is different from all other sets in Table 2, by being a multi-layer set, it is presented here as a sub-critical example (representing the classic joint system in the Appalachian Plateau).

Table 3 contains ten rock examples from eight fracture provinces and is divided into two fracturing groups: While joints cutting thick Palaeozoic sandstone formations in east and northeast Sinai, Egypt, as well as in thick Jurassic sandstones from Utah, USA, which are exclusively marked by rib marks (Fig. 2f) (Table 3: items 1–3), joints in magmatic rocks are decorated by both plumes and arrest marks (items 4–10).

The examples from the magmatic provinces represented by items 4–6 are different from the other joints given in Table 3 by their appearances. They occur between close boundaries that limit their sizes. Their height is limited in the basalt between close, horizontal boundaries (DeGraff & Aydin 1987; item 4), their width is confined parallel to vertical joints (Bahat 1991: 145; item 5), and the joints cutting the granitoid formed between earlier sub-horizontal joints (Fig. 2f; item 6).

The abundance of plumes in granitoids (items 7–10) repeatedly occurs on large joint surfaces in different jointing provinces, at the Bohemian Massif from the Czech Republic and at the Knowles and El Capitan from the Sierra Nevada in California, is unlimited between close, earlier joints (e.g. Bahat et al. 2005: 326, 335, 338, 342; Fig. 2g).

2.2 Joints that formed unstably

Table 4 contains six technological materials (1–6), which were fractured in the laboratory, three rocks that were blasted in quarries (7–9), and five examples of rocks (10–14) that were cut by joints, which formed under dynamic geological conditions, representing three fracture provinces (the Mrákotin post critical examples are distinguished from the Borsov post critical ones, and the latter is not counted in Table 4 as a new province, since this outcrop also appears in Table 3).

Thus, Tables 2–4 represent altogether 19 jointing provinces. The three rock fractographies that were formed in quarries by blasts (Table 4) are not counted as fractured provinces, because they formed by non-geological processes.

This chapter addresses the post critical fracture propagation of materials from five groups (Table 4).

The first group (items 1–3) represents fracture in various glasses, demonstrating hackles on their fringe (Fig. 3a) and the lack of rib marks and plumes on their mirror planes. This fractography was obtained by blasting glass bottles (Bahat et al. 1982).

The second group (items 4–6) represents fracture in various ceramics and metals (e.g. Price et al. 1991). Mirror planes of such fractures occasionally display radial striae but not concentric rib marks, and often arrest marks and plumes are entirely absent (Fig. 3b), resembling such surfaces in glasses (Fig. 3a; e.g. Rice 1974, also Bahat et al. 2005: Fig. 2.33a, Rice 1984: Figs. 3 and 24). The hackles in the fringe are typically of the “cuspate” nature, similar to the one obtained in blasted rocks (the third group: items 7–9; Fig. 3c). These fractures often show mirrors without arrest marks or plumes similar to those of fractured glasses, resembling fractured ceramics (Fig. 3b). Thus, common to the above three groups are hackles in the fringes and relatively smooth mir-

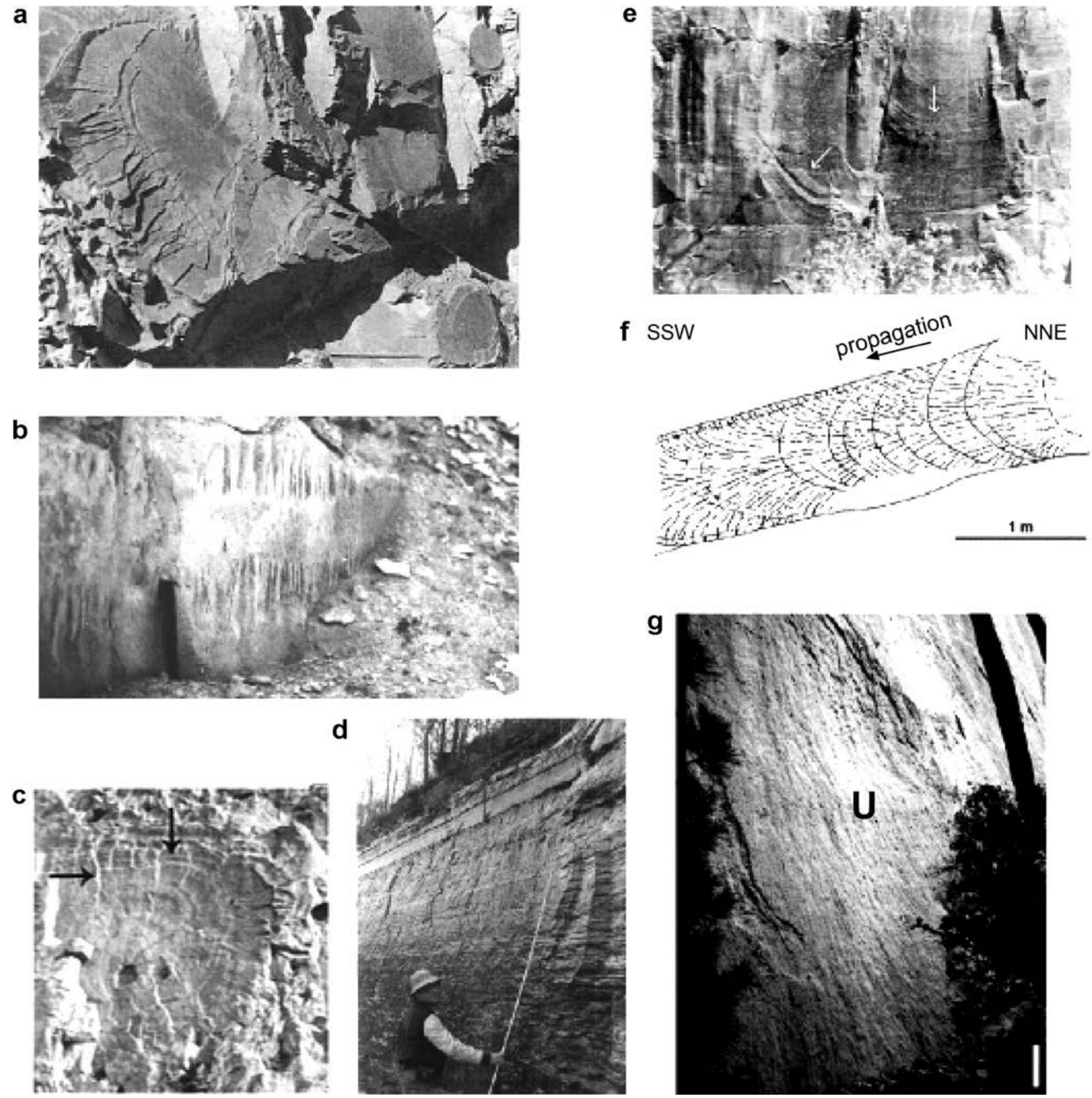

Fig. 2: (**a**) Fractography of joints cutting flint clay under syntectonic conditions, in the Ramon anticline, Israel. Joints decorated by mature fractographies that show both arrest marks and plumes occurring next to smaller joints (lower right), which reveal only arrest marks (no plumes); scale is 15 cm (from Bahat 1991: Fig. 3.42). (**b**) A delicate plume (mostly erased) and two fringes of en echelon, above and below the parent joint, cutting Middle Eocene chalk near Beer Sheva; bar = 15 cm. (**c**) Both arrest marks (vertical arrow) and plumes-striae (horizontal arrow) decorate the cross fold joints that cut the Cretaceous dolostone near Jerusalem; width of joint is about 1 m (modified from Weinberger 2001). (**d**) A large arrest mark occurs on a joint surface, which cuts shales (strike 346°) next to Terry Engelder (from Bahat 1991: 218). (**e**) Different characteristics of ripple marks, undulations – vertical arrow, and arrest marks – inclined arrow on post uplift joints from the Navajo Sandstone Formation in Zion National Park, Utah, USA; width of right joint (with vertical arrow) is about 4 m (see further on definitions in Bahat et al. 2005: 128). (**f**) Drawing of joint J1 from the Borsov quarry, showing some twelve arrest marks superposed by a plume. The fracture markings are confined in a “wedge” between two sub-horizontal earlier joints boundaries. (**g**) A coarse, vertical plume undercuts thin slices from the back wall of an arch (in both sides of the plume) at the foot of El Capitan cliff; the sidewall of the arch is shaded at right. The smooth curved undulation “u” maintains orthogonal relation with the plume; white scale at lower right is 30 cm.

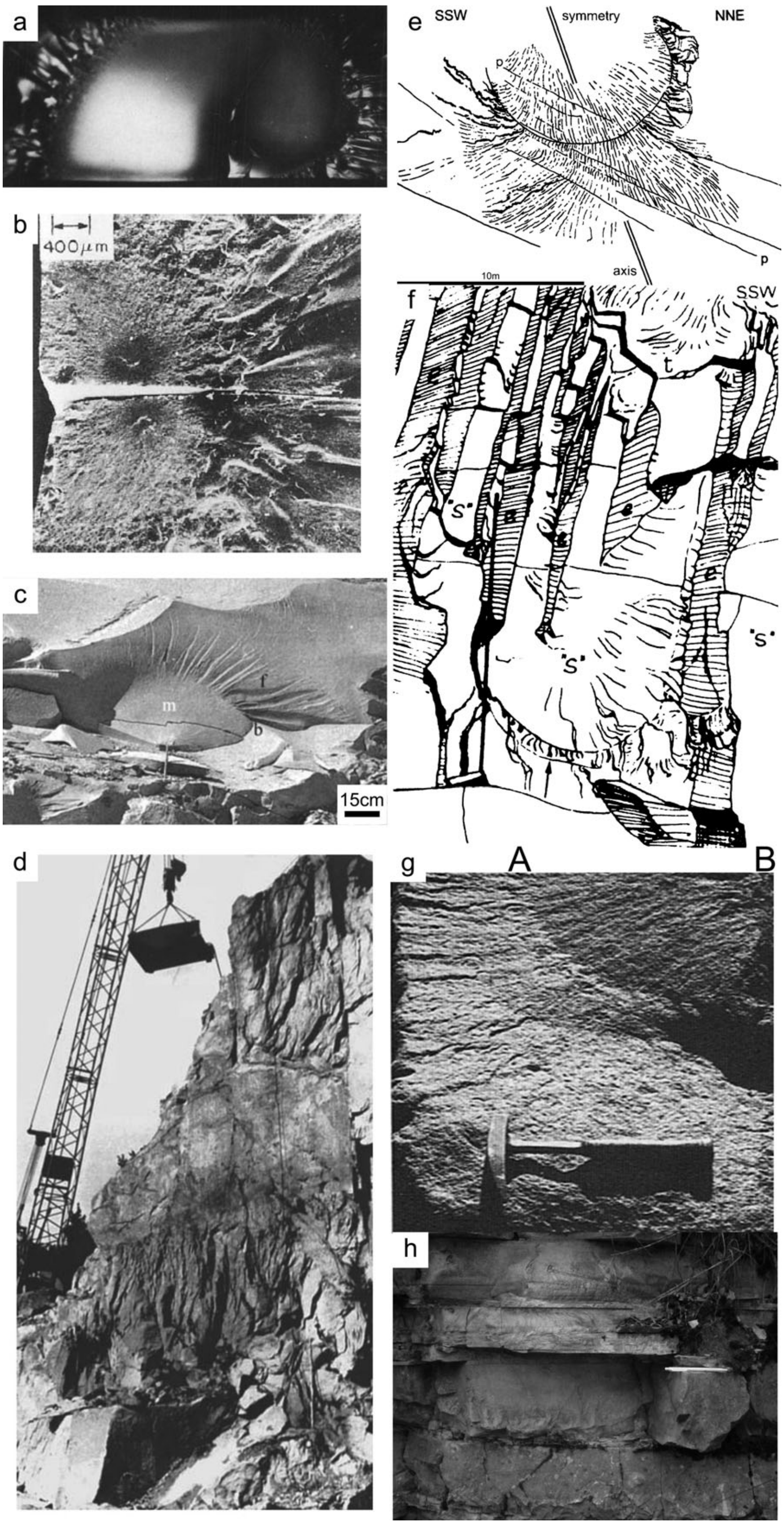

Fig. 3: (**a**) A smooth mirror plane of a fractured glass bottle, rimmed by a hackle rough fringe; thickness of the fractured piece (i.e. vertical distance in photo) is 3 mm (Bahat et al. 1982). (**b**) The origin at the centre of a smooth, dark mirror plane, and distinct sharp hackle ridges. These are termed "cuspate hackles" and appear on two matching halves of a fracture of $BaTiO_3$ (from Rice 1974). (**c**) A "joint" formed by road blasting near Ma'alot in northern Israel, reveals a mirror m, and a hackle fringe f, forming an angle between the two, along the mirror boundary b; a pencil 10 cm long shows the origin of fracture (after Bahat et al. 2005: Fig. 2.30b). (**d**) A joint from the Mrákotin quarry, showing a smooth mirror plane and hackle fringes above and below it. A secondary mirror sm forms at the fringe; scale is two metres (after Bahat et al. 2005: Fig. 4.11a). (**e**) A drawing of joint J8 from the Borsov quarry, which shows a mirror plane that has a downward facing circular mirror boundary and a fringe with a heterogeneous morphology: almost no fringe relief close to the symmetry axis, a non-uniform en echelon fringe at left and a hackle sector at right; diameter of the mirror plane is approximately 10 m (after Bahat et al. 2003). (**f**) A part of the left side of a unique en echelon fringe of joint J9 (the "trefoil joint" marked as "t"). "e" and "s" are en echelon segments and steps, respectively. A downward facing "secondary mirror" "sm" is unconventionally formed on a composite surface made of several en echelon segments and steps, and its boundary and fringe are marked by a vertical arrow; the vertical scale at left is 2 metres (after Bahat et al. 2001b). (**g**) An uplift joint in granite from eastern Sinai. Fracture initiation at A. Curve B marks the circular mirror boundary. Note radial striae between A and B and hackles fanning out beyond B; distance from A to B, r = 360 mm. (**h**) A single layer joint cutting Solnhofen limestone, showing a smooth mirror plane rimed by cuspate hackles at its lower side (arrowed); white scale is 15 cm.

ror planes, with occasional radial striae, but not concentric rib marks. These are characteristic features of unstable fracturing.

The fourth group (items 10–13) represents four fractures in plutonic rocks from natural outcrops. Like in rapidly fractured glasses, arrest marks and plumes are hardly or not at all visible on their mirror planes and hackles reside in the fringes (Fig. 3d). Hence, the fracture surfaces of these rocks contain fractographic information indicating rapid fracturing (Bahat 1991: 231, Bahat et al. 2005: Figs. 2.56 and 4.11).

The fractography of item 11 shows an uncommon fringe, which is divided into three sectors (Fig. 3e): No segmentation around the symmetry axis, en echelon like cracking of no uniform sizes and shapes on the left side of the axis, and hackling on its right side. The fractography of item 12 exhibits a "secondary mirror" on its complex en echelon fringe (Fig. 3f). The uplift joint from Sinai is shown in Fig. 3g (item 13).

The mirror boundary that distinguishes between the inner mirror plane and outer hackle fringe is quite clear in all items of Figs. 3a–h). The unique secondary mirror plane sm shown in Fig. 3d is a particular manifestation of dynamic fracturing (Bahat et al. 2001b, 2003). This secondary mirror represents the initiation of a bifurcation, which is an advanced stage of the dynamic process (b in Fig. 4).

An important parameter is the tilt angle ϕ, which the mirror plane makes with the fringe (insert to Fig. 1a; also seen, although not measured beyond the mirror boundaries of Figs. 3a–h, particularly in Fig. 3c). This is an additional criterion for identifying a rapid fringe (Bahat et al. 2001b, see particularly Bankwitz & Bankwitz 2004), since in stable slow en echelon fringes, ϕ always equals zero. The ϕ angle is not identified in item 12, because this fractography was photographed at 90° to the fracture surface, so that its profile could not be examined (Fig. 3f).

The fifth group (item 14) represents a rare occurrence of a cuspate hackle in the fringe of a joint cutting the Solnhofen limestone in Southern Germany (Fig. 3h). Cuspate hackles occasionally occur in fringes of rocks that formed by blasting. They are analogous to common hackles in fringes of fractured ceramics, and occasionally display coarse morphologies in fractured rocks (Bahat 1991: Fig. 3.60c).

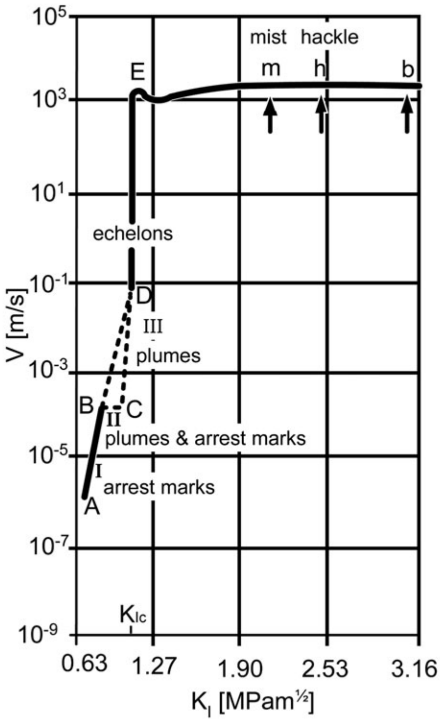

Fig. 4: The V versus K_I curve for joints in the Borsov granite synthesised from combined experimental results and calculated nine criteria, where letters A, B, C, D and E present locations at which fracture mechanic conditions change (detailed in Bahat et al. 2003). Descriptions in small letters (like arrest marks) indicate their approximate fractographic positions along the curve. The location of D is the position of the fracture toughness $-K_{Ic} = 1.09$ MPam$^{1/2}$. The letter "b" marks the location of initial branching.

3. Discussion

The interpretations of the observations from Tables 2–4 are presented first, then they are followed by a debate on stable vs. unstable jointing, ending in a Table 5 that summarizes Tables 2–4.

3.1.a Joints that formed stably – presented in Table 2

1. The difference between the two stages of propagation, from the embryo one to the mature jointing is recorded in the flint clay (Fig. 2a), which is uncommon among many other rocks. In flint clay, which is a soft and weak rock, only the cross fold joints were found. Apparently, the orthogonal stress, which should have occurred due to stress relaxation (Rives et al. 1994), was not sufficient to create strike joints. Thus, the rather slow fracturing in this somewhat plastic and weak rock in this province has resulted in a drastic differentiation in the two orthogonal directions (Bahat 1991: 183–186).

2. A strong differentiation between early cross fold joints and late strike joints, cutting chalks under syntectonic conditions (Weinberger & Bahat 2008), characteristically resulted in the ladder pattern (Fig. 1b), also termed the H pattern (Hancock 1985). This pattern is associated with a fractographic differentiation between the two orthogonal directions, reflecting corresponding stress differentiation: Plumes that decorated the cross fold joints propagated faster due to greater stresses and fracture velocities than arrest marks that decorated the strike joints by induced smaller stresses. Hence, differentiation between fracturing in the two orthogonal directions is exhibited differently in the two provinces (items 1 and 2). In both provinces extended periods separated between deposition and fracturing: The Santonian chalk was jointed during the Late Senonian (Weinberger & Bahat 2008; about late fracturing of the flint clay see below).

Table 2: Fractographic features on single layer joints that formed stably in sedimentary rocks. The Table shows eight provinces. The two descriptions from upstate New York (items 8 and 9) represent one province. The question mark in the 8th column of province 5 implies uncertainty regarding the split of the Middle Eocene chalks into two provinces (4 and 5 in Table 2).

1	2	3	4	5	6	7	8	9	10
#	**Cross joints Azimuth Fractography**	**Strike joints Azimuth Fractography**	**Joint type**	**Joint class**	**Joint relationship**	**Lithology**	**Fracture province**	**Particular features**	**Source**
1	Arrest marks & plumes set ~320°	Joints less common set ~050°	Single layer	Syntectonic	Sub orthogonal	Flintclay	Jurassic Ramon anticline Israel	Delicate plumes	Bahat (1980a)
2	Plumes Set 316°	Arrest marks set 050°	Single layer	Syntectonic	Ladder pattern in sequence	Chalk	Santonian Judean desert Israel		Weinberger & Bahat (2008)
3	Arrest marks & plumes set 328°	Arrest marks & plumes set 59°	Single layer	Burial	Grid pattern, alternation	Chalk	Lower Eocene Northern Negev Israel	Coarse plumes	Bahat (1988)
4	Plumes set 012°–035°	No joints	Single layer	Uplift	Joint rotation	Chalk	Middle Eocene Northern Negev Israel	No orthogonal jointing Delicate plumes One fringe	Bahat et al. (2005): 153
5	Plumes set 350°–014°	No joints	Single layer	Uplift	Joint rotation	Chalk	Middle Eocene Northern Negev Israel?	No orthogonal jointing Delicate plumes Two fringes	Bahat et al. (2005): 153
6	Rare fractography no mirror planes		Single layer	Syntectonic	Joint rotation Ladder pattern	Limestone	Jurassic Bristol Channel UK	Coarse plumes on thin layers	Roberts (1974, 1995), Rawnsley et al. (1998), Engelder & Peacock (2001)
7	Arrest marks & plumes set ~280°		Single layer	?	Later, another set ~345°	Dolostone	Cretaceous central Israel	Striae type plumes	Weinberger (2001)
8	Plumes set 333°	No joints	Single layer	Burial	Joint rotation	Siltstone	Devonian upstate New York, USA	Three plume types	Bahat & Engelder (1984), Younes & Engelder (1999)
9	Arrest marks set 346°	No joints	Multi- layer	Syntectonic	Joint rotation	Shales	Devonian upstate New York, USA		Bahat & Engelder (1984), Younes & Engelder (1999)

3. Jointing in the Lower Eocene chalks took place mainly during the Lower Eocene and resulted from alternating stresses in the orthogonal direction (in a given rock layer) under burial conditions (Bahat 1989). It is characteristically manifested by the grid pattern (Fig. 1c). This pattern is associated with only a partial fractographic differentiation between the two orthogonal directions: Arrest marks are about the same in the two orthogonal directions, although there is a relative scarcity of plumes along the strike joints. Thus, a comparison of the two provinces (items 2 and 3) shows the association of the ladder pattern with syntectonic jointing and the grid pattern with burial jointing. Possibly the two orthogonal forms represent alternating stress and stress relaxation. However, the differential stresses were significantly greater during the syntectonic stage than during the burial one.

4. and 5. Set 012°–035° formed in an association with the uplift and rebound of the Beer Sheva Syncline in a rotational

Table 3: Fractography on joints that formed stably in thick sedimentary formations and in magmatic rocks. The Table shows eight provinces. The two descriptions from Sinai (items 1 and 2) and from California (items 9 and 10) represent one province in each case. ⇓ Downward propagation direction, ⇑ upward propagation direction, and ⇐ ⇒ horizontal propagation directions of fractographic features.

1	2	3	4	5	6	7	8	9
#	**Fractographic features**	**Propagation directions**	**Joint type**	**Joint class**	**Lithology**	**Fracture province**	**Particular features**	**Source**
1	Arrest marks	⇓	Multilayer	Uplift	Sandstone	Paleozoic East Sinai Egypt	Orthogonal sets	Bahat (1980b)
2	Arrest marks	⇒	Multilayer	Uplift	Sandstone	Palaeozoic Northeast Sinai Egypt	Orthogonal sets	Bahat (1979)
3	Arrest marks	⇓⇑	Multilayer	Post uplift	Sandstone	Jurassic Utah, USA	On strike joints	Bahat et al. 2007
4	Plumes	⇐ ⇒	Between horizontal boundaries	Cooling joints	Basalt	Columbia River Plateau, USA	Columnar joints	DeGraff & Aydin (1987)
5	Plumes	⇑	Next to a vertical boundary	Cooling joints	Basalt	East African rift, Kenya	No layering	Bahat (1991)
6	Arrest marks & plumes	⇐ ⇒	Between earlier horizontal joints	Cooling joints	Granodiorite	Borsov quarry, south Bohemian pluton, Czech Republic	On S type joints	Bahat et al. (2003)
7	Plumes	Radial	Concentric	Cooling joints	Granodiorite	Bohemian Massif, Czech Republic		Bahat et al. (2005): Fig. 4/17d
8	Plumes		Oblique joints	Uplift	Granodiorite	Knowles California, USA		Bahat et al. (2005): Fig. 4/17a
9	Plumes & rib marks	⇓		Post uplift	Granodiorite	El Capitan California, USA	Lower height of cliff	Bahat et al. (2005): 338
10	Plumes & rib marks	⇓⇑		Post uplift	Granodiorite	El Capitan California, USA	Middle height of cliff	Bahat et al. (1999)

manner. On the other hand, set 350°–014°, was possibly created much later by N–S stresses in connection with the Dead Sea Rift (Bahat et al. 2008b). Their delicate plumes have been interpreted to reflect relatively great fracture velocities, under tensile conditions caused by uplift(s), compared to the coarse plumes that reflect relatively slow propagation in the Lower Eocene chalks. The question mark in the 8th column of province 5 implies uncertainty regarding the split of the Middle Eocene chalks into two provinces (4 and 5 in Table 2). Assuming that the connection between delicate plumes, uplift conditions, and relatively faster fracture propagation, still in the quasi-static stage (Bahat et al. 2008a) is applicable to fracture in the flint clay, it would suggest that actual fracturing took place not before the Jurassic sediments in the Ramon Anticline have uplifted and approached the ground surface, perhaps, sometime in the late Tertiary (Picard 1943).

6. On jointing and fractography in the Lias limestone, see below in the section connected with Table 4.

7. The fractography that decorates the joints, which cut the Cretaceous dolostone near Jerusalem (Fig. 2c), is quite different from the fracture markings on the joints in the Solnhofen Jurassic limestone, probably suggesting different fracture conditions. Quite likely, the lack of hackles in the fractography of the Cretaceous dolostone indicates fracturing under less intense conditions than in the Solnhofen Jurassic limestone, which occasionally is decorated by coarse, cuspate hackle fringes (Fig. 3h).

8. and 9. Quite intriguingly, even though under syntectonic condition, the arrest marks in the shales (set 346°, Fig. 2d) indicate slower propagation than the joints in the siltstone (set 333°), which formed under burial conditions in the Appalachian Plateau. This seemingly paradoxical observation (because fracturing under syntectonic conditions is expected to be more intense than under burial conditions) is resolved by the presence of the very long siltstone intercalation within the shale that reveals a spectacularly long plume

Table 4: Fractography induced by rapid, unstable fractures in brittle technical materials and rocks. The Table shows three provinces (items 10, 13, 14). The other items are artificial (1–9) or already appear in Table 3 (items 11, 12). In this text the term "granitoids" implies variations in granodiorites.

1	2	3	4	5	6	7
#	**Material**	**Method of fracture**	**Fractography on mirror plane**	**Fractography on fringe**	**Location (province)**	**Source**
1	Glass	Tensile	Not visible	Hackle	Laboratory	Holloway (1973)
2	Glass soda-lime	Tensile	Not visible	Hackle	Laboratory	Bahat (1979)
3	Glass pyrex	Tensile	Not visible	Hackle	Laboratory	Unpublished
4	$BaTiO_3$ polycrystal ceramic	Tensile	Not visible	Hackle	Laboratory	Rice (1974)
5	Tungsten-carbon alloy	Tensile	Not visible	Hackle	Laboratory	Rice (1984): 9
6	SiC body	Tensile	Not visible	Hackle	Laboratory	Rice (1984): 35
7	Limestone	Blasting in quarry	Not visible	Hackle	Ma'alot northern Israel	Bahat (1991): 208
8	Limestone	Blasting in quarry	Few striae are visible	Hackle	Kent south England	Bahat (1991): 208
9	Metamorphic	Blasting in road quarry (blasthole)	Not visible	Hackle	Pennsylvania, USA	Bahat (1991): 209
10	Granitoid	Thermally stressed jointing during late cooling of the rock	Not visible	Hackle	Mrákotin quarry, south Bohemian pluton, Czech Republic	Bahat et al. (2005)
11	Granitoid	Thermally stressed jointing during late cooling of the rock	Visible	Hackle and En echelon	Borsov quarry, south Bohemian pluton, Czech Republic	Bahat et al. (2003): J8
12	Granitoid	Thermally stressed jointing during late cooling of the rock	Almost not visible	En echelon secondary mirror	Borsov quarry, south Bohemian pluton, Czech Republic	Bahat et al. (2003): J9
13	Granite	Uplift jointing non insitu	Radial striae	Hackle	Central Sinai, Egypt (Precambrian)	Bahat (1991): 231
14	Limestone	Syntectonic single layer	Rare	Hackle uncommon	Solnhofen, South Germany	Bankwitz et al., unpubl.

(Bahat 1991: Fig. 3.18). It implies faster propagation of jointing in the intercalation than in the host shale. This observation implies that under given stress conditions a fracture would propagate faster in the more elastic siltstone than in the associated plastic shale, which absorbs much of the fracture energy.

Joint rotation occurred in the Middle Eocene chalk from the Northern Negev (items 4 and 5) as well as in the siltstone and shales from the Devonian in the Appalachian Plateau (items 8 and 9). However, in these two locations the fracture mechanisms were different. In the Middle Eocene chalk joint rotation was associated with a corresponding stress rotation linked to the uplift and rebound in the Beer Sheva Syncline (Bahat et al. 2005: 274), while in the Devonian sediments joint rotation was associated with large scale rotation in tectonic stresses (Younes & Engelder 1999). No orthogonal jointing, which was confined to a particular rock, was observed in any of the three lithologies. However, orthogonal jointing does appear in the combined lithologies of the Devonian sediments, one direction in the siltstone and another direction normal to it in the shales, which stratigraphically alternate the siltstone. Whereas the joints formed by uplift in the chalk are decorated only by delicate plumes, implying uniform fracturing, the joints cutting the siltstone that formed under burial conditions display a variety of plume types, suggesting variable fracturing conditions (Bahat & Engelder 1984).

In summary, although the fractographies presented in Table 2 are highly variable, they all record stable fracture propagation.

3.1.b Joints that formed stably – presented in Table 3

The data in Table 3 relate to two topics: (1) fractographies that form on large fractured surfaces in rocks, and (2) fractographies that form between close boundaries in magmatic rocks (about 1 metre apart, e.g. Fig. 2f).

While arrest marks conspicuously mark large fractured surfaces in sandstones (items 1–3, Fig. 2e), plumes are fairly common on fractured surfaces in magmatic rocks (items 4–10, Fig. 2g). Occasionally the plumes occur with arrest marks or undulations (items 6, 9, 10, Fig. 2f).

Ideally, when all relevant information is available, one should compare joints in different rock types that belong to the same joint class (Tables 2 and 3), assuming that stresses should be different in the environments, which control the different classes. Also, in this context differing rock strengths should be taken into account. However, since the scope of the present introductory work is still limited, comparisons are confined to the available data.

Within this limited scope, there could be several alternative interpretations for these fractographic differences. First, joint propagation velocities were generally lower in the sandstones, which has high porosity and is more fragile than the hard granitoids and basalts. Second, mixed modes I and III are more conducive in creating striae in the magmatic rocks, while mixed modes I and II are more advantageous in forming arrest marks in the sandstone rocks. Third, considering that these rocks have different strengths, the value of the fracture stress divided by the rock strength, was lower for the sandstones than for the magmatic rocks. Hence, the effective fracture stress was lower in the sandstone than in the magmatic rocks, which enabled slower rock fracturing under lower stresses in the sandstones.

Without excluding the first two interpretations, the third one seems to get more support. There are many observations that correlate the type of joint fractography with the magnitude of stress (e.g. Bahat et al. 2003, Weinberger & Bahat 2008). It also corresponds well to the distinction between the fractographies exhibited in the lower part of El Capitan Cliff, compared to the middle height of this cliff (items 9 and 10, respectively), which implies that different local fracture conditions in the same lithology resulted in different fractographies: Apparently, due to buckling, tension was greater in the middle height then in the lower height of the cliff (Bahat et al. 1999).

Possibly, support for the above interpretation comes also from the following: The rates of uplift were greater in the magmatic provinces than in the sandstone provinces given in Table 3, i.e. the tectonic history of these magmatic rocks was more intense than the corresponding one for the sandstones, and consequently the uplift was faster in the southern part of Sinai, where the Precambrian basement is exposed, than further north, where Palaeozoic sediments occur at the surface. An investigation of the uplift rate confirms this differentiation (Kohn & Eyal 1981).

There are certain appearances of plumes in magmatic rocks, which are particularly fascinating. Previous studies on sedimentary rocks have shown that plumes occur prevalently in thin layers (Roberts 1961) and, for unclear reason, are absent on joints cutting thick formations (e.g. Bahat et al. 2005: 261). Their presence in cooling basalts between close, horizontal boundaries (DeGraff & Aydin 1987; Table 3: item 4), or next to vertical joints (item 5), and between sub-horizontal earlier joints in granitoids (Bahat et al. 2003; item 6, Fig. 2f) suggest an analogy to the general appearance of plumes on thin, single layer joints occurring in sedimentary rocks and mud-cracks (Weinberger 1999).

None of the fractographies presented in Table 3 include hackled fringes. Hence they record stable fracture propagation.

3.1.c Joints that formed unstably – presented in Table 4

The first five material groups in Table 4, including the glasses (items 1–3), the ceramics and metals (items 4–6), the blasted rocks (items 7–9), the granitoids from the Bohemian Massif, as well the granite from Sinai (items 10–13), and the Solnhofen limestone (item 14), all these fractographies display two common features: They are tensile fractures, which show mirror planes that practically lack arrest marks, and many such fractures also do not have plumes imprinted on them. Also, they are decorated by hackles on their fringes (Fig. 1a and Figs. 3a, b, c, d, g, h). Hackles in the fringe of fractured materials provide a strong criterion of rapid fracture under post-critical conditions. This dynamic regime is shown on the right side of K_{IC} on the K_I versus V plot (Fig. 4), while K_I is a measure of the ratio of the maximal stress concentration near a flaw to the nominal stress. In an infinite plate under remote tension, σ_0, having a sharp flaw of length c, expressed as $K_I = \sigma_0 (\pi c)^{1/2}$.

While the hackle clearly indicates unstable fracturing in the Mrákotin quarry (item 10, Fig. 3d), the two fractographies from the Borsov quarry (items 11 and 12, Figs. 3e, f) suggest an unstable fracturing, based on other considerations. An unstable propagation is interpreted for item 11 because of its complex fringe that contains a sector of hackling (Fig. 3e). The unstable fracturing of item 12 is suggested by the velocity cycling of this joint (Bahat et al. 2001a) and by its "secondary mirror plane" sm in the fringe (Fig. 3f).

It may be argued that the fringe of joint J10 (J1–J10 are denoted joints from Bahat et al. 2003: Fig. 14) does not represent hackling, instead it shows a local set of joints that looks like hackles around J10 (Engelder 2007). While at the fringe facing the reader, its central part looks like a group of several actual joints. However, at the left and right sides of this group there are fracture zones of very low spacing, in which the cracks are conspicuously disoriented to all directions, a typical attribute of hackle zones. Hence, the large fringe of J10 seems to be mostly a hackle.

The rarity of fractography on the joint surfaces on the one hand, and the intriguing cuspate hackles, which occasionally decorate fringes in the Solnhofen limestone (Fig. 3h), seem to suggest that at least some of the single layer jointing in the Jurassic limestone from Southern Germany occurred rapidly. If so, the latter fractography possibly implies that some jointing occurred close to the ground surface following uplifting, because such conditions would promote relatively strong tensile stresses, which may promote rapid fracturing. Alternatively, excessive local pore pressure could induce intense fracturing at great depths (Secor 1965, Bahat et al. 2003). Such conditions should independently be established regarding the Jurassic limestone from South Germany.

3.2 Stable vs. unstable fracturing of rocks

This issue is particularly intriguing. Engelder (2007) in his chapter termed "The Mrákotin granite controversy" argues against the findings of Bahat et al. (2003). He questions, "… whether or not it is possible to recognize fracture mirror and mist on joints (i.e., critical and post-critical rupture)…". However, Bahat et al. (2003, and associated publications) did not consider mist on joint surfaces. Nobody has ever seen mist in fractured rocks, because this delicate structure is camouflaged by the rock grain boundaries. On the other hand, the mirror and mirror boundaries may be well established on joint surfaces (e.g. Bahat et al. 2001a, b, Bahat et al. 2005: 140, 307). The main thrust of the paper by Bahat et al. (2003) was to show a gradual transition of the stress intensity, K_I and velocity, V of fracture propagation in the Borsov Quarry, via changes in their fractographies (present Figs. 2f, 3e, f). These series indeed show that the majority of joints at the Borsov quarry suggest sub-critical propagation (item 6, Table 3), but only few joints imply post-critical conditions (items 11 and 12, Table 4, Figs. 3e, f). It does not fit the claim by Engelder (2007) "…that joints in the Borsov Quarry carry a mirror hackle surface morphology indicative of unstable, critical and post-critical rupture".

Engelder (2007) stresses "…that not even a small fraction of thousands of stress measurements in the Earth should have detected tensile stress of the type that would have driven joints in the Mrákotin granite to unstable velocities". Perhaps he should have added to this statement that, while these measurements relate to current stresses in the cold crust, the joints investigated by Bahat et al. (2003) in the Mrákotin granodiorite were formed "between 320 and 330 Ma (Bankwitz et al. 2004, Gerdes et al. 1998)", under stresses that could be greater during the late stage cooling of the water rich rock. Indeed, Engelder's debate regarding tensile fracturing at great depths is not with Bahat et al. (2003), but with the theory of fluid overpressure by Secor (1965).

A conclusion by Engelder (2007) is that: "…stable, subcritical crack growth is the dominant mechanism for opening mode crack development in the brittle crust of the earth". This is probably correct for most rocks. Bahat (1979) suggested that "Most joints are expected to have been at least partly developed by mechanisms of slow crack propagation under static or dynamic loads", with the implication that even under dynamic loads the resistance to jointing in the crust by the lithostatic weight plays a dominant role in slowing down the process of jointing for almost all joint classes (Table 1). Perhaps one outstanding exception is jointing in cooling granitoids (Fig. 3d), which occur under extreme hot water pressures. But there are additional, natural dynamic mirror planes like Figs. 3e–h. Still intriguing is the difference between the very rough fringe of the Mrákotin granitoid (Fig. 3d) and the moderate fringe of the granite from Sinai (Fig. 3g): What were the different conditions of dynamic fracturing in these two cases?

4. Classification of joint provinces

The above comparative study of jointing and fractography in 19 distinct provinces was based on the data assemblage in Tables 2–4. The main characteristics that are given in these tables are summarised in Table 5, which may be viewed as a generalised classification of joint provinces.

This classification may be useful in two ways. Firstly, like all other classifications (e.g. the Periodic Table) it provides a systematic arrangement of all elements and encourages further systematisation of forthcoming data. Secondly, there is a clear connection between the uniform direction of the strikes of the NNE oriented late cooling joints from the South Bohemian Pluton province and the earlier, larger country rock structure in the South Bohemian Pluton (Bahat et al. 2003). Also, in the general NNW–NW orientation of the elongated Sierra Nevada Batholith, the NNW–NW joints in the batholith formed perpendicular to the main horizontal compression that created the Permian or Triassic synclinorium and related axial structures (Bateman & Wahrhaftig 1966), which subsequently controlled the formation of these fractures in the Sierra Nevada plutons. Furthermore, Lockwood & Moore (1979) found that the direction of maximum horizontal extension strain in the Sierra Nevada Batholith varies between WNW and NW, precisely fitting this model. The two examples, from central Europe and western USA demonstrate that an identification of a joint province can lead to the discovery of hidden ancient structures at great depths, geographically linked to the province (Bahat et al. 2005: 352, 354).

Table 5: Classification of joint provinces; based on data in Tables 2–4, according to three categories.

Categories of joint provinces	Formed stably in single layer sedimentary rocks		Formed stably in thick sedimentary formations and in magmatic rocks	Formed unstably occasionally, in plutonic rocks and rarely in sedimentary rocks.
Typical joint relationships	Orthogonal couple	Ladder pattern	Multilayer joints in sandstones. “Single layer” joints in basalts. Uplift and post-uplift joints in cooling granodiorites.	Strikes of joints cutting granodiorites on cooling correspond to early country rock structures.
		Grid pattern		
	Single	Strike rotation		
		Unique strike		
Characteristic fractographies on mirror plane and fringes	Arrest marks and plumes in partial mirror planes		Exclusive arrest marks occur in thick sandstone formations. Exclusive plumes are common on volcanic rocks. Both fractographies appear in post-uplift granodiorites.	Plumes and arrest marks are rare on full mirror planes. Hackles are on fringe of some cooling grano-diorites and uplift joints in granites.
Distinct from the other two categories	Joints form stably, exclusively in thin sedimentary layers		Joints form stably in thick sedimentary formations and magmatic rocks.	Hackles decorate fringes, indicating unstable fracturing.
Sources	Table 2		Table 3	Table 4

5. Future research

It is currently suggested that the arrest marks, which decorate many sandstones, compared to plumes, which almost exclusively mark magmatic rocks (Table 3), reflect distinct tectonic conditions. The validity of this thought depends on further studies that would exclude the notions that under a given stress and rock conditions joint propagation velocity would be lower in sandstones than in magmatic rocks, or that mixed modes I and III are more conducive in creating striae in magmatic rocks, while mixed modes I and II are more advantageous in forming arrest marks in sandstone rocks.

6. Conclusions

(1) There are strong differentiations of fracturing in the two orthogonal palaeostress directions that induced jointing in the Jurassic flint clay from the Ramon and in the Santonian chalk from the Judean desert (Table 2: items 1 and 2, respectively). In both cases the fractographies suggest faster fracturing in the cross fold direction than in the strike direction. This differentiation is far more pronounced in the Santonian chalk than in the Jurassic flint clay, possibly because they represent syntectonic and uplift jointing, respectively.

(2) Joints that formed in the Santonian chalk from the Judean desert under syntectonic conditions resulted in the ladder pattern, whereas jointing that occurred in the Lower Eocene chalk from the Northern Negev (Table 2: items 2 and 3, respectively) under burial conditions displays the grid pattern.

(3) In the ladder pattern jointing was associated with plumes, marking the joints along the cross fold direction, and arrest marks forming along the strike direction. On the other hand, the grid pattern jointing displays both markings on joints along the two orthogonal directions.

(4) The joint rotation in the Middle Eocene chalk (Table 2: item 4) is linked with three additional attributes: (i) delicate plumes that formed by (ii) jointing under uplift conditions, and (iii) lack of orthogonal jointing.

(5) The joint rotation in the Devonian sediments from the Appalachian Plateau in upstate New York (Table 2: items 8 and 9) lacks orthogonal jointing in a given lithology. However, the cross fold joints in the siltstone beds and strike joints in the shale alternating beds are orthogonally related.

(6) Under given stress conditions, fractures could have propagated faster in the intercalated, more elastic siltstone than in the thick plastic shales alternating the siltstone, which absorbed much of the fracturing energy in the Devonian sediments from the Appalachian Plateau.

(7) Jointing in the Cretaceous dolostone from central Israel (Table 2: item 7) differs from the above mentioned groups: It does not occur in orthogonal sets and there is no joint rotation.

(8) This study shows that while arrest marks conspicuously mark joints in thick sandstone formations (Table 3: items 1–3, Fig. 2e), plumes almost exclusively decorate the magmatic rocks (items 4–10), possibly because fracturing in the sandstones was exposed to lower stresses than in the magmatic rocks.

(9) The horizontal plumes that propagated between “layer boundaries” some 10 cm apart (Table 3: item 4) suggest that the local sub-horizontal boundary conditions prevailed over the cooling stresses that were induced in the basalt while fracturing. Analogically, close boundaries of earlier sub-horizontal joints induced plumes in granitoids (Table 3: item 6, Fig. 2f).

(10) Tensile failure in glasses, ceramics, blasted rocks and naturally fractured granitoids (Table 4: items 1–12 and 14) display two common features: smooth mirror planes that practically lack arrest marks and only rarely plumes imprinted on them, while their fringes are decorated by hackles. These features indicate unstable fracturing.

(11) The rarity of fractography on the parent joint surfaces and the hackles, which occasionally decorate fringes in the Solnhofen limestone (Table 4: item 14), suggest that the single layer jointing in this province occurred relatively rapidly, partly in the dynamic regime. There are not yet observations of analogous hackles in the Jurassic limestone from the Bristol Channel (Table 2: item 6), but their possible existence should not be ruled out.

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