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**Investigation of Exfoliation Joints in Navajo Sandstone
at the Zion National Park and in Granite at the Yosemite
National Park by Tectonofractographic Techniques**

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ABSTRACT

Tectonofractographic techniques have been applied to the study of joint exfoliation in the Navajo sandstone at Zion National Park and in the granite at Yosemite National Park. New types of fracture surface morphologies have been observed which enabled the discerning of incipient joints and consequent fracture growth in these rocks.

Incipient jointing in the sandstone is mostly manifested by elliptical and circular fractures (meters to tens meters across) initiating from independent origins. They interfere with each other and grow to larger circular fractures producing exfoliation surfaces up to hundreds of meters across. Less frequently, series of large concentric undulations demonstrate the propagation of a large fracture front producing exfoliation from an individual origin. One such fracture front reveals refraction of undulations at a layer boundary.

On many occasions incipient fractures of different size are fringed by en echelons. Several en echelon styles have been elucidated. Certain en echelon fringes surround the joint mirror plane with well defined rims of en echelons and hackles which enable the determination of the tensile fracture stress, σ_f . For a joint with a mirror plane having a rim of a non uniform width populated by hackly en echelons of various lengths, values of σ_f vary from 0.8 MPa to 2.0 MPa when fracture surface energy $\gamma = 2.54 \text{ Jm}^{-2}$ data derived from quartz crystals are used in the calculations. This mirror is thought to be the consequence of rapid fracture and the results fit quite well experimental data. On the other hand, for a joint with a mirror plane having a rim of approximately uniform width populated by regular en

echelons of approximately similar lengths, results for σ_f vary from 1.0 MPa to 2.5 MPa using $\gamma=88 \text{ Jm}^{-2}$, a value derived from sandstone. This mirror plane is considered to have been mostly developed by a fatigue fracture, but the propagation attained high velocity during the late fracture stages.

The mechanism of fracture growth from incipient circular fractures repeats itself on each new exfoliation joint. Subsequent such joints develop further inside into the rock, maintaining parallelism to the previous surface, and normality to the minimum principal stress.

Arches in Zion national Park are ubiquitous in shape and size, revealing stages in their evolution by a mechanical process, which was associated with exfoliation, but independent of local faulting. Exfoliation and arching mostly occurred on vertical surfaces of N-NNW and NE sets of prominent joints, but there are also deviations from this general trend. Exfoliations surrounded by arches are commonly younger than others and provide fresher exposures to study early stages of jointing. Several such exposures were carefully measured by electronic surveying technique. The N-NNW joint system can possibly be divided into two distinct sets.

In Yosemite National Park large exfoliations (hundreds of meters in size) developed on the El Capitan cliff by the interaction and merging of many previous smaller incipient joints that vary in size from meters to tens of meter. Here the incipient joints have the shape of partial distorted fans defined by radial plumes (striae) that initiated at distinct origins and were bounded at the other end by concentric undulations. These fans grew in all directions and formed larger joints parallel to previous surfaces. Another mechanism of growth of large exfoliation joints was the propagation of single fracture fronts, as revealed by their fracture morphologies. Results for σ_f vary from 0.1 MPa to 0.4 MPa using $\gamma=4.06 \text{ Jm}^{-2}$ derived from microcline for an exfoliation which is considered to be for its most part a product of a fatigue fracture process.

Introduction

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Fracture exfoliation in the massive sandstones of the Colorado Plateau in general, and at Zion National Park (ZNP), in particular, has attracted many investigators (e. g. Gregory, 1950; Holman, 1976). This phenomenon also intrigued people investigating granites in Yosemite National Park (YNP) (Cadman, 1969; Holman, 1976), and in New England (Jahns, 1943; Johnson, 1970). The "tantalizing similarity" in shape of various fracture properties that occur in both the Zion and the Yosemite canyons has attracted many geologists (Grater, 1945; Bradley, 1963). Vertical exfoliation seems to be more predominant in ZNP whereas exfoliation on the flanks of domes is more prominent and has attracted more attention in YNP. The terms exfoliation (Cadman, 1969) and sheeting (Holman, 1976) have been used interchangeably by many investigators in describing these phenomena.

Although it is clear that exfoliation in ZNP occurred parallel to earlier surfaces, two major questions have not yet been settled. Firstly, do exfoliation joints curve to remain faithful to the new valley sides, independent of the earlier regional joint sets (Bradley, 1963) ?. It seems to us that they do not just parallel walls of old entrenched meanders (Nelson, 1979) but there is, rather, a relationship between the earlier vertical prominent joints - or in short prominent joints, of which many of the cliffs are made, and later exfoliation which is connected mostly with the vertical cliffs. Less common exfoliation occurs at various attitudes, and is associated with previous surfaces not related to the cliffs. Secondly, did the prominent joints strongly develop along only one azimuth (Grater, 1945; Robinson, 1970) or, are they regionally arranged in two series, trending N 20 -30 W and N 70 -80 E, the former being the prominent one (Gregory, 1950) ?

The origin of exfoliation in rocks has been debated since Gilbert's (1904) theory connecting sheeting with the expansion of the rock body in response to unloading

by erosion. This subject has been discussed along two main lines: 1) The natural mechanisms involved, including thermal processes like contraction of magma by cooling, or ground surface temperature fluctuations, regional tectonic stresses, differential weathering, and consequent residual stresses (Holzhausen, 1989), and, 2) The stress conditions close to the ground surface causing the exfoliation, concentrating on the high compressive stresses which parallel the ground surface (Dale, 1923, p. 34).

A few interpretations regarding stress conditions that were suggested are mentioned below. Fracture develops when critical stress difference occurs between the principal stresses parallel to the surface (White, 1946). The magnitude of these compressive principal stresses is sufficiently large so that additional stresses would be able to fracture the rock under cyclical biaxial loading (Cadman, 1969). Residual compressive stresses are responsible for these developments (Bradley, 1963; Holman, 1976). A net tension normal to the surface may occur under certain conditions (Bridgman, 1938; Holman, 1970; Holzhauser, 1977), or the third principal stress is near zero (Holzhauzen, 1989). The maximum principal strain theory is useful in certain variations in the analysis of exfoliation joints (Cadman, 1968; Holman, 1976). See further discussion on exfoliation in Holzhausen (1989).

Arches in the ZNP are thought by Gregory (1950) to be primarily the result of erosion. Recently, Cruikshank and Aydin (1994) offered the explanation that in Arches National Park in south eastern Utah arches were produced by localized erosion that occurred at zones of intense fracturing due to shear on existing discontinuities. Robinson(1970) on the other hand, theorized a process of mechanical failure to be the cause for large arches in the Zion canyon.

Fractography is a method for the analysis of fracture surface morphology and their causes and mechanisms in technological materials. Tectonofractography

applies fractographical analysis to rock fractures with the objective of identifying the tectonophysical processes that produced the fracture and determining the mechanical conditions involved. These techniques have been applied to sheet fracture and exfoliation joints so far only to a limited extent. Robinson (1970) considers them to be weathering scars. Holman(1976) observed them in the Yosemite park. Holzhausen(1989) pointed out their importance, particularly regarding the significance of the en echelon segmentation on granitic sheet surfaces, and suggested that exfoliation forms by rapid unstable propagation . Bahat (1991a, pp. 149 and 234) showed fracture markings containing concentric undulations and a plume and radial hackles on a sheet joint. He correlated fracture surface morphology of joints to crack velocity and stress intensity parameters. In this context hackles generally implied intense fracture.

Apart from its scientific interest, exfoliation has practical applications. Exfoliation reflects a general tendency of the rock to fracture parallel to a previous surface if stresses allow, and hence, is crucial in tunneling and along boreholes, because these types of openings suffer from occasional unstable cracking parallel to newly created surfaces. Exfoliation is also an important consideration in road and dam construction and maintenance. Carefully planned excavation procedures, based on exfoliation data, can overcome some acute safety problems and economic losses (Niles, 1871; Cadman, 1969; Holzhausen, 1989). Exfoliation fractures are central in some hydrological projects related to waste isolation / remediation where accurate characterization of the fracture system is important (e.g. Cohen , 1993). Exfoliation cliffs are spectacular to tourists in the national parks, and en echelon exfoliation penetrated quite impressively into the arts and architecture (see for example, the walls at the "Revelations" in Yerba Buena Gardens, San Francisco).

Objectives

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Studying incipient fractures which develop into exfoliation joints, and the growth modes of the latter in ZNP and YNP is the main objective of this investigation. In studying exfoliation we shall use tectonofractographic techniques. We shall aim at determining local fracture stress conditions of several joints in these parks, and elaborate on en echelon fractures which occur in a wide variety in the ZNP. Arching in various styles is part of the exfoliation process in both parks, particularly in ZNP. We shall measure a few such representative structures with a high precision technique.

Implications of morphological microstructures (structures which result from various space relationships of fracture markings) to other scientific fields will be considered. The definition of the terms sheeting and exfoliation, and the distinction between sheet fractures and layer boundaries will also be addressed. Since much of the understanding of exfoliation fractures and the geomorphology of the canyons in ZNP depends on their linkage to earlier major jointing, we shall start with reexamining the regional distribution of the major joints in the ZNP and their relationship to the main topographic features. We shall study exfoliations on both vertical cliffs and sloping surfaces.

Techniques and procedures

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Regional fracture

A study of the regional joint distribution was carried out, upon which the more detailed outcrop investigation in ZNP was based. A tributary map of an area 10 km by 13.5 km in the ZNP was prepared by tracing the blue creek markings on the Springdale East and the Temple of Sinawana quadrangles of the USGS topographic 1:24000 maps (1980). The azimuths and lengths of 92 straight tributary segments

were then measured on the new map. A straight segment was defined as one which fitted a frame 1 mm wide and at least 12 mm long (equivalent to 300m long).

The spacing between 38 adjacent and approximately straight N-NNW tributaries were measured on the tributary map. The map was divided into 4 sub-horizontal zones (Fig. 4) and spacing between the two closest tributaries was determined separately in each zone, so as to avoid measuring a particular tributary twice. An approximately straight creek was defined as one that would fit a frame 3 mm wide and longer than 30 mm (equivalent to 750 m long). The statistical results are summarized in four histograms.

Different jointing styles from incipient fractures to full size joints as well as arches are documented in photographs and diagrams. Grids and scales for certain diagrams and associated photographs are based on measurements in the field either by a tape measure or electronic surveying (Figs. 6e,7c,8d,9c,10b,10g) whereas for others (Figs.3a-3d;6a,b,6f-6i,10d,e) size magnitudes are approximate.

Electronic Surveying

An electronic total station with a laser range - finder provided the means to survey points on cliff faces. For each cliff face, measurements were taken from two base stations. From the first station readings of azimuth and elevation angles were taken. This was done for several points. Extensive, high resolution photographs were also taken. The surveying instrument was then set up again, about 300 meters away (at the same distance from the cliff). To allow for distance triangulation, bearings were taken for three of the points, selected to give a good representation of the cliff face.

Bearings on the key points that were taken at both locations were then analyzed to give true XYZ position of each point via triangulation. The three points form a plane which is taken to represent cliff face. The bearings for the other points were utilized as ray vectors emanating from the station location. The point of intersection

of these rays with the plane representing the cliff face comprises the approximate XYZ position of the point. These points were then plotted on the plane of the cliff face. In addition to measuring features directly from this plot, comparison with photographs allows additional measurements to be taken accurately from additional features.

The principal caveat in this approach lies in the assumption that the cliff is flat. For the geometries used, a deviation of 3 meters from flatness yields an error in calculated position on the cliff of at most one meter. However, this does not appear to be a problem, as the relief on these cliffs is generally less than 3 meters, and the distances measured are on the order of 50 - 100 meters, yielding an error rate of only 1-2 %, which is entirely acceptable for the use at hand.

Geology

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The Zion National Park

The ZNP occurs in south western Utah (Fig. 1a) and is part of the Markagunt Plateau which is bounded to the west by the Hurricane fault, and its eastern edge is marked by the Sevier fault (Grater, 1945). The distance between these faults in the southern part of the park is about 60 km. The Markagunt Plateau is situated at the transitional area between the the Colorado Plateau and the Basin - Range province (Kurie, 1966), at the western side of the Colorado Plateau.

The present study concentrates on exposures of the Navajo Sandstone in the ZNP. This unit is about 400-600m thick in the canyon area, and is thought to be of Middle Jurassic age ? (Fig. 1b). It is a massive, fine-grained, friable, equigranular quartz sandstone (Grater, 1945; Gregory, 1950).

The Markagunt Plateau was uplifted by a slow and intermittent movement

Fig. 1.a.

Figure 1.a. Location map of Zion National Park and Yosemite National Park.
 b. Stratigraphy of the Navajo sandstone in the Zion Park area (after Gregory, 1950).

Fig. 1.b.

(Grater, 1945). According to Kurie (1966) uplifting occurred by the Hurricane zone of normal faults which sliced parallel to the approximately N-S Laramide Kanara anticline in late Cenozoic time, totaling upward displacement of about 1300m. The uplift took place in two major stages, on two subparallel fault traces.

The prominent regional joints are thought to have developed during this period of uplift (Grater, 1945). Gregory (1950) discovered that straight parallel tributaries to the main canyon took advantage of prominent joints. He also suggested that the joints are small scale expressions of stresses that have produced the regional uplift and such zones of fracture as the Hurricane and Sevier faults. Bradley (1963) observed exfoliation in sandstone formations throughout the Colorado Plateau. He considered that most exfoliation joints are probably of Pleistocene age.

The Yosemite National Park

Regional fractures striking N-NW and E-NE in sets approximately perpendicular to each other are abundant in the Sierra Nevada batholith (Becker, 1891).

The geochronology, field relations and hydrothermal mineral assemblages together suggest that these fractures formed between 85 and 79 Ma, soon after the host pluton was emplaced (Segall et al., 1990). Lockwood and Moore (1979) found that the direction of maximum horizontal extensional strain changes systematically from north to south, and main strain directions at WNW and NW are remarkably parallel to late Mesozoic to present-day tectonic extension directions in the Basin and Range province. Westward tilting of the Sierra Nevada block occurred in late Tertiary time. Various investigators (e. g. Lockwood and Moore, 1979) have shown that regional fractures similar to those generally known from the Sierra Nevada batholith exist in YNP (Fig. 1a).

Huntington (1966) and Holman (1970) found that sheeting developed most abundantly in quartz monzonite and granite, spottily in granodiorite, and never in quartz diorite or gabbro. The reason for it is not yet known.

Cliffs produced by the prominent joint sets are very impressive in the YNP, but they are not as systematic as in the ZNP. They are more closely geographically associated with the main canyon along the Merced river, and parallel tributaries that follow prominent joints at considerable distance from the main canyon are rare in YNP.

Fracture surface morphology

Woodworth (1895, 1896) set the stage for the science of fractography by astute observations of the fracture morphology on joint surfaces in geological exposures. De Freminville (1907, 1914) elaborated considerably on the various fracture markings. Parker (1942) and Hodgson(1961a, b)brought this almost dormant subject to the attention of geologists. Bahat (1991a) updated this subject.

Following fracture initiation at discontinuities, fracture propagates in the rock through a great number of disturbances with material heterogeneities and interfering stresses and emanating waves. These disturbances are recorded on the fracture surface by characteristic fracture markings (Fig. 2). Additional to the markings in figure 2 , an important fractographic feature is the en echelon segmentation (Woodworth, 1896;Hodgson, 1961; Bankwitz, 1965, 1966;Pollard et al., 1982).

In most cases however, only one or several of these "finger prints" can be identified on the fracture surface. But, based on these finger prints a trained geologist may derive from it useful information on the fracture history.

Figure 2.

Figure 2. Schematic representation of a fracture surface showing the: fracture origin at initial flaw, critical flaw from which unstable fracture may occur, mirror plane, radial striae, concentric undulations (ripple marks), Wallner lines, mist, hackle, and r_m the mirror radius. On natural exposures only few of these fracture "finger prints" appear.

Results obtained at the ZNP

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Prominent joints in the ZNP

Prominent fractures in the ZNP mostly strike NNW or NE (see elaboration by Gregory, 1950). They form the cliffs in the park and their exposed portions may reach hundreds meters in length and height. They are mostly vertical and straight (Fig. 3a), and quite often the NNW and NE joints cut each other into orthogonal or sub orthogonal rectangular blocks (Fig. 3c).

An unusual feature in the ZNP is the N-NNW series of approximately straight tributaries, subparallel to each other and reaching lengths of some 2000m and more. An examination of these tributaries on the 1:24000 scale topographic maps reveals that many of them are deep and narrow canyons (tens meters across). These canyons are characterized by large vertical walls formed by prominent joints (Fig. 4). What previously appeared to be fracture zones in these canyons (Gregory, 1950) are basically individual prominent joints with parallel series of late exfoliation joints.

The length distribution of straight N-NNW tributary segments is wide (Fig. 5a), with a special emphasize in the 375-525 meter range. Occasionally, two or more segments represent a single, approximately straight tributary. There is a narrow spread of the azimuths of straight segments (Fig. 5b), pointing to a peak at 346°-347° (N14°W-N13°W). A weaker peak occurs at 356° (N4°W), possibly indicating a second NNW joint set of lesser importance. Two regional joint sets differing only some 10° are known from the Appalachian Plateau (Sheldon, 1912). The N-NNW oriented prominent joints are clearly identified on aerial photographs (Gregory 1950).

This joint system does not align with the main canyon produced by the Virgin River, or any arrangement pointing to a possible structural dependence on any of

Figure 3.a.

Figure 3. Major fractures in the Zion National Park:

a. Close-up look at a lower part of a vertical N-NNW prominent joint in the Hidden Canyon, showing two vertical en echelon segments (marked A), each one is on the order of several meters high and up to 1 meter thick, close to the bottom. Right stepping en echelon segments, each individual several meters long and several centimeter thick (B), at the top of picture. At the center, supperposing a segment of the A series is en echelon array (C) with inclined stepping tens centimeters long and tens millimeters thick spreading upward from a single center. Note sub horizontal layering of the sandstone undisturbing the en echelons.

Figure 3.b.

Figure 3. Major fractures in the Zion National Park.
b. Jointing in the Weeping Rock. The wall which is on the order of 300 meter height is divided by a sheet fracture. In the upper part a NE joint set dividing the rock into thick slabs deviating from verticality. They arrest at the sheet. On the surface of the NW joint below the sheet note many crescents convexing downward.

Figure 3.c.

Figure 3. Major fractures in the Zion National Park.
c. Orthogonal jointing of prominent joints at the Temple of Sinawava. The surfaces sub-parallel to picture are NE oriented, and the joint at the left sub-normal to picture strikes NNW. Their horizontal lengths are in the order of 10 meters.

Figure 3. Major fractures in the Zion National Park.
d. A vertical exfoliation surface fractured by a series of small niches at lower center, and a nich some 20 meter long which developed to a small arch at upper center (arrowed). A series of partial arches and en echelons at left.

Figure 3.d.

Figure 4.

Figure 4. Tributary map in ZNP. Angle Arch, Red Arch, Lady Mountain, Weeping Rock, Hidden Canyon, Springdale, and Zion Lodge are designated respectively, by A.A., R.A., L.M., W.R., H.C., Sp. and Z.L. Dash-lines represent tributaries and point-lines are boundaries of the main canyon. SHZ are four sub horizontal zones for measuring spacing between two closest tributaries.

Figure 5.

Figure 5. Histograms summarizing data on length, spacing and azimuth of prominent joints along tributaries in ZNP:

- Lengths of straight N-NNW tributary segments.
- Azimuths and cumulative lengths of straight N-NNW tributary segments.
- Azimuths and cumulative lengths of straight NE tributary segments.
- Spacing of approximately straight N-NNW tributaries.

the main canyon features. The narrow canyons, however, form along prominent joints.

The narrow canyons are fewer than the number of prominent joints revealed in aerial photographs or observed in outcrops. Their spacing varies considerably, mostly in the range of 270-1400 meters (Figs.4 and 5d). Often they are "hidden canyons" separated topographically from the main canyon of the park.

There are also NE oriented prominent joints occurring as vertical walls, occasionally producing sub-orthogonal relations with the N-NNW joints. The NE joints spread in orientation (Fig. 5c) and they are generally shorter. They play only a minor role in creating narrow canyons. On the 1:24000 topographic maps they are recognized as short straight elevation lines several mm long (tens to about a hundred meters long).

Tectonofractography

Most of the common fractographic features that have been observed in rocks (Fig. 2) occur in Zion park. There are also fracture surface morphologies unknown from previous studies. Some of the markings are displayed in such details, which enable new qualitative and quantitative interpretations of the exfoliation phenomena. These are presented below.

Incipient circular fractures. Many vertical and non-vertical fracture surfaces are marked by series of incipient circular and/or elliptical fractures (ICF). The diameters of these fractures vary from tens of centimeters to tens of meters (Figs 6a-d). These ICF often occur parallel or sub - parallel to each other on the same plane, and interfere with each other in a variety of styles. Some share common boundaries, others penetrate into each other, and occasionally a small circle is engulfed by a larger one, so that several ICF produce a larger exfoliation joint (Figs. 6a-f).

Figure 6.a.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.
a. Photograph of a series of adjacent incipient fractures, described in Figure 6.b.

Figure 6.b.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.

b. Diagram of a series of adjacent incipient circular fractures of different shapes on an exfoliated joint surface. Fracture A interacts with an elliptical fracture B below. Fracture A is cut by two long vertical right stepping en echelons that merge into the en echelon rim below A. Fracture B is combined of two smaller earlier incipient fractures and the en echelon rim below B followed this merging. There are some three incipient fractures x, y, z, along the contact between A and B. There are more incipient fractures around A and B. Some of them are marked by letters m-p. The height of ellipse B is on the order of 4 m.

Figure 6.c.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.
c. Photograph of the Angle Landing Arch (in short, Angle Arch).

Figure 6.d.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.
 d. Diagram of Angle Arch photograph based on detailed measurements of the arch and incipient circular fractures surrounded by the arch. Measurements were not taken from the exact location from which the arch was photographed, therefore, certain parts appear somewhat different on diagram and grid. Note arrowed undulations on side - wall.

Fig. 6.e.

Fig. 6.f.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.
 e,f. Photograph and diagram of a very large circular exfoliation joint A, having a diameter on the order of 100 meters, inside which there is an internal exfoliation surface. Note on the internal surface a circular incipient fracture B. The dark streaks on the external exfoliation (drawn as three sub-parallel lines) do not appear in the circular fracture on the internal exfoliation. On the lower left side of the external exfoliation there is a small incipient ellipse C surrounded by a larger incipient ellipse D. Two additional ICF are observed.

The annular periphery of various ICF are marked differently. In some fractures the periphery is fully circular and uniform. In others, certain parts of the periphery cut deeper than others into the rock, or are missing. Often ICF extend upward and produce crescent niches (convexing upward) between the external slice and the slice internal to it (Fig. 7). There are also crescents which concave downward (Fig. 3b). Characteristically, the upward convexing crescents mostly appear in the shade, whereas the downward convexing crescents mostly are bright.

Radial plumes (striae). Incipient fractures may be decorated by various markings. Radial striae are common. Their importance is in pointing out the location of fracture initiation and the mode of fracture propagation. Occasionally there are radial striae on a nich (Fig. 7b), the only part remaining from the ICF. Striae occur as either straight or distorted individuals often in radial arrangements, or as strands partly straight and occasionally bent. As radial features, they may cross mirror boundaries into hackle rims (Fig. 8c, d).

Concentric undulations. Concentric undulations (ripple marks) appear in a variety of styles on exfoliation surfaces. Occasionally they display a propagation style quite different from the more common mode of fracture growth by interacting ICF. Groups of many large undulations may record wide individual fracture fronts sweeping parallel to previous joints and producing "families" of exfoliation joints. A spectacular series of more than 40 such ripple marks occur on the western wall of the Hidden Canyon, covering an area tens of meters by tens of meters (Fig. 6g). Here, several almost identical vertical fracture fronts advanced horizontally from south to north and created two or three parallel exfoliations, one internal to the other. This exemplifies a most probable contemporaneous exfoliation process at different internal distances from the surface of the rock, yet controlled by a single mechanism. In this outcrop the fracture crossed layer boundaries and the

Fig. 6.g.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.

g. Undulations whose length is on the order of 80 meters, convexing sidewise to the right.

h. Undulations whose length is on the order of 20 meters, convexing downward.

Fig. 6.h.

Figure 6.i.

Figure 6. Fracture surface morphology of exfoliation joints in ZNP.
i. Side - wall of a partial arch with downward convexing undulations indicating downward fracture propagation. One upper undulation (also termed hesitation line) coincides with a layer boundary which influenced the location of the hesitation line. See rappelling person (arrowed) for scale.

Figure 7.a.

Figure 7.a. Photograph of a series of fracture markings on the cliff striking NE at Lady Mountain. Note previous exfoliation slices at left.

Figure 7.b. An enlargement of part of Figure 7.a.

Fig. 7.b.

Figure 7.c. Diagram of Figure 7.a.. Letters A and B indicate series of upward convexing niches, C and D are two series of en echelons, exfoliating sidewise to the left producing partial arches.

Fig. 7.c.

undulations produced a continuum across these boundaries. This boundary crossing, however, was associated with refraction of the ripple marks.

Two series of undulations convex downward on two adjacent prominent joint planes. The joints are separated by an orthogonal vertical fracture (Fig. 6h). The left undulations arrest at a horizontal sheet fracture implying that the surface marked by the undulations is younger than the sheet fracture.

En echelon fracture. En echelon fractures are ubiquitous on exfoliation surfaces, and they occur in various styles and scales. Characterization of en echelons includes the determination of the sense of stepping. The determination of stepping is done when the observer looks along the propagation direction of the steps from the shoulder or from the mirror boundary along the radiating directions of the cracks (Fig. 8c). Right stepping will be recognized when the sequence of "shingles" appears to rise toward the observer's right.

We divide the en echelon population into two general groups. The first group consists of the common series of parallel en echelon segments which exfoliate in a uniform azimuth and maintain a uniform spacing on a particular vertical joint. They normally occur in series of vertical "shingles" (Fig. 3a), ranging in thickness from 0 to tens of centimeters, and are oriented at small angles (less than 20°) with respect to the surface into which they penetrate. Often they are associated with ICF and/or niches from which they had developed.

These fractures appear in a nice display on the cliff facing northeast at Lady Mountain (Fig. 7a, b). An early stage of this structure is shown by two series of little crescents (A and B in Fig. 7c), which we term niches. In A, they occur near each other at about the same topographic elevation, and in B, they appear one above the other. Some niches are marked by radial striae (Fig. 7b; note also B in Fig. 7c). A further fracture propagation occurs following the development of ICF. Quite often

this propagation is sidewise, when two or more ICF grow into a series of en echelons (C and D). The series of thick slices at the left side of the cliff are remnants from earlier exfoliations. Adjacent en echelon series of different scales maintaining similar strikes and stepping (Fig. 3a) are not uncommon in the Zion park. It suggests that localized stress conditions are responsible for the development of these en echelons, possibly exerted at different times.

En echelons in radial arrangements constitute the second group. They most commonly occur as "disorganized" curved fringes which surround ICP or larger fractures (Fig. 6c). Less frequently they appear in concentric rims which surround mirror planes. Two rim types are distinguished in the latter group. The first type consists of large rims (tens of meters of arcuate length) which maintain approximately uniform width, and en echelon segments of approximately equal lengths arranged in a well defined shingle-like superposition (Fig. 8a, b). The second type is represented by small en echelon rims (a meter or several meters of arcuate length) whose widths vary and the en echelons hackle into various shapes, width and length. In certain parts of the rim, hackles are longer than in others (Fig. 8c, d) reflecting areas of fracture under higher stress intensity conditions (Bahat, 1991a, p. 209). As far as we know, such a distinction has not been observed before in either geological outcrops or in fractured technological materials. Our calculations (in a forthcoming section) demonstrate a correlation between mirror and rim properties, and fracture stress conditions.

Fracture stress =====

We quantified the fracture stress σ_f of two fracture surfaces that revealed to us en echelon rims which surrounded mirror planes. We applied the two methods used by Bahat and Rabinovitch (1988). We first calculated the σ_f of a fracture surface which occurs along the trail leading to the "Hidden Canyon" (Fig. 8c, d). The rim of this fracture consists of radial hackles resembling fracture surfaces of technological

materials derived under laboratory conditions. The second analyzed fracture surface is the large mirror bounded by the Red Arch (Fig. 8a, b). In this fracture, the rim of en echelons is of a uniform shape maintaining a constant width.

The fracture surface along the trail to the "Hidden Canyon"(the H. C. fracture)

The well curved hackle rim is in very good condition showing an abrupt boundary with the mirror (Fig. 8c). We first have to obtain the mirror radius r . The location of the fracture origin is uncertain, so that r is determined on the basis of the sinus law. The measured distance AB between the two tips of the hackle rim (Fig. 8d), $2y=2.24\text{m}$, and the normal to AB, from C to D, $x=0.54\text{m}$. According to the sinus law $z/\sin\alpha=2r$ where α is the angle produced by AB and AD, and z is the distance between A and D. Since $z^2=x^2+y^2$, $r=x^2+y^2/2x$, and hence $r=1.43\text{m}$.

First method. We calculated the fracture stress σ_f on the basis of the relationship (Randall, 1966):

$$\sigma_f = K_{Ic} \sqrt{Q} / \sqrt{1.2\pi C_{cr}}, \quad (1)$$

According to Atkinson and Meredith(1987, Table 11.3) the critical stress intensity factor K_{Ic} for sandstones varies from $0.34 \text{ MPam}^{1/2}$ to $2.66 \text{ MPam}^{1/2}$. We took the average value of the five results for sandstones qualified by Atkinson and Meredith (under their category c), and obtained $K_{Ic} = 1.0 \text{ MPam}^{1/2}$. The modifying geometrical factor Q ranges in value from 1.0 for a long shallow flaw to 2.46 for a semi-circular flaw (Randall, 1966). Since we do not know the shape of the flaw, we used an average value $Q=1.73$. We derived the radius of the critical flaw C_{cr} from $r/C_{cr} = \text{constant}$. This is an acceptable constant for fracture mirrors in ceramics, which varies from 13.9 to 16.7 (Mecholsky and Freiman, 1979). We used for this ratio the value $r/C_{cr} = 15.3$, and obtained $C_{cr} = 0.093\text{m}$. Hence the result for the fracture stress $\sigma_f = 2.2 \text{ MPa}$.

Figure 8. En echelons and hackles in radial orientations. a. Photograph of Red Arch. A concave downward arch. Note at lower part en echelon rim with a uniform width (arrowed), partly concealed at left by previous exfoliation slices.

Fig. 8a.

Figure 8.b. Diagram of Red Arch. The series of A and C points describe earlier large and small arches, respectively; the B series represents an ICF and the D series follow the contours of the main arch. Numbers I, II, III, represent the boundary of fracture mirror with rim, and IV and V are the lower boundary of rim in the main arch.

Fig. 8.b.

Fig. 8.c.

8.d.

Figure 8. En echelons and hackles in radial orientations.

c. Photograph of a mirror plane on an exfoliated joint along the trail to the "Hidden Canyon". The radial striae in the mirror are individually irregular, but, they are arranged in an en echelon style. Note the sharp circular boundary between the mirror and the rim. The hackles at the rim have different lengths and shapes along the rim, yet, they maintain an overall en echelon arrangement. The hackles maintain a uniform left stepping, whereas the striae are right stepping in the lower part of picture and left stepping in the upper one.

d. Diagram of mirror plane in c. ADB is the boundary between mirror below and rim above. Measured distances in the field: $2y=2.24$ m and $x=0.54$ m. Note slight ellipticity in the circle.

Table 1: Determination of fracture stress, σ_f on exfoliation joints

First method	The Hidden Arch Zion National Park				Red Arch Zion National Park			
Parameters	r (m)	c_{cr} (m)	K_{Ic} $MPa\cdot m^{1/2}$	σ_f MPa	r (m)	c_{cr} (m)	K_{Ic} $MPa\cdot m^{1/2}$	σ_f MPa
Results	1.43	0.093	1.0	2.2	31.9	2,085	1.0	0.5

Second Method

Parameters	r (m)	γ (Jm^{-2})	G	γ (Jm^{-2})	G	r (m)	γ (Jm^{-2})	G	γ (Jm^{-2})	G
	1.43	2.54	$2\sqrt{2}$	$5\sqrt{2}$	88	$2\sqrt{2}$	$5\sqrt{2}$	2.54	$2\sqrt{2}$	$5\sqrt{2}$
						31.9				
σ_f (MPa)			0.8	2.0				4.7	11.7	
								0.2	0.4	1.0
										2.5

First method

Parameters	Fracture SW of Half Dome Yosemite National Park			
	r (m)	c_{cr} (m)	K_{Ic} $MPa\cdot m^{1/2}$	σ_f MPa
Results	96.43	6.30	1.9	0.59

Second Method

Parameters	r (m)	γ (Jm^{-2})	G	γ (Jm^{-2})	G
	96.43	4.06	$2\sqrt{2}$	$5\sqrt{2}$	0.69
			$2\sqrt{2}$	$5\sqrt{2}$	
σ_f (MPa)			0.14	0.37	
					0.06
					0.15

Second method. For the calculation of σ_f , we applied an expression which directly takes the mirror radius into account (Congleton and Petch, 1967):

$$\sigma_f = 2G\sqrt{E\gamma} / \sqrt{\pi r} \quad (2)$$

where G is the enhancement factor which varies from $2\sqrt{2}$ to $5\sqrt{2}$. We calculated for these two values. According to Turcotte and Schubert (1982, p. 432) values for Young's modulus of sandstones vary from 10^{10} Pa to 6×10^{10} Pa. We used an average value, $E = 3.5 \times 10^{10}$ Pa. We averaged six fracture surface energy results obtained by different methods for quartz by Hartley and Wilshaw (1973), Brace and Walsh (1962) and Atkinson and Avdis (1980), see Atkinson and Meredith (1987, Table 11. 1). This average is $\gamma = 2.54 \text{ Jm}^{-2}$. We also used the value $\gamma = 88 \text{ Jm}^{-2}$, obtained by Perkins and Krech (1966) for Tennessee sandstone. For $\gamma = 2.54 \text{ Jm}^{-2}$, we obtained the σ_f values 0.8 MPa and 2.0 MPa, when the enhancement factors $G = 2\sqrt{2}$ and $G = 5\sqrt{2}$, were respectively used. For $\gamma = 88 \text{ Jm}^{-2}$, the respective results (for $G = 2\sqrt{2}$ and $G = 5\sqrt{2}$) were $\sigma_f = 4.7$ MPa and $\sigma_f = 11.7$ MPa.

Robinson (1970) gives four results for tensile strength of Navajo sandstone cores derived by uniaxial tension tests. For two cores parallel to bedding results were 3.0 MPa and 1.2 MPa, and for two cores normal to bedding 0.5 MPa and 1.0 MPa values were obtained, averaging about 1.4 MPa. Hence, the present results derived by the two methods are in good agreement with experimental results, with the exception of the results obtained by the second method for the fracture surface energy values of the Tennessee sandstone, which were too high.

The fracture surface bounded by the Red Arch

We calculated the fracture stress responsible for the development of the mirror plane inside the Red Arch on the basis of the radius r of the circle which produced the en echelon rim at the bottom of the mirror (Figs. 8a, b). Parameters of the rim were measured (Fig. 8b). We applied the same procedure used for calculating σ_f for

the H. C. fracture. Accordingly, r was calculated to be 31.9 m. The result by the first method is $\sigma_f = 0.5$ MPa. The two results by the second method using $\gamma = 2.54 \text{ Jm}^{-2}$ are $\sigma_f = 0.2$ MPa and $\sigma_f = 0.4$ MPa, and when using $\gamma = 88 \text{ Jm}^{-2}$ we obtained $\sigma_f = 1.0$ MPa and $\sigma_f = 2.5$ MPa, see Table 1.

Arches

The characterization of ICF is basically a two dimensional analysis of an individual surface. A study of en echelon phenomena concerns deviations at small angles (less than 20°) of fracture propagation from the surface into the rock. The investigation of arching in the ZNP is in most part related to series of exfoliation fractures which sequentially developed parallel to each other advancing in columns along the third dimension into the rock. The rock exfoliation into a series of fractures and corresponding series of parallel rock slices provide the starting conditions for the development of arches.

Arches occur by the hundreds in ZNP, in various shapes. A full shape arch concaves downward and consists of a ceiling and two side - walls. A partial arch lacks one side - wall or/and part of the ceiling. Height of arch opening is measured from base to ceiling, and width of opening is measured between opposite side - walls at the base. Sizes of arches vary from several meters to many tens of meters (Figs. 6d and 8b, and Table 2).

An arch in its miniature manifestation is a crescent nich concaved downward (Fig. 7a-c). The nich may further propagate sidewise and produce en echelon fracture (Fig. 7) which may later develop into partial arches (Figs. 7 and 3d), or may develop into a full shape small or medium - size arch which cuts across a single exfoliated slice.

The fracture occurs along an arcuate trajectory according to a mechanism similar or identical to the one proposed by Robinson (1970). He modeled the arch as a plate

with semicircular hole at the base, subjected to uniaxial vertical compression, and determined the stress distribution around it. He found that the rock above the center of the arch is under tension and would tend to fail along arcuate surfaces. Robinson's suggested mechanism is supported by two repeated observations: Firstly, the contours between the slice and side - walls and ceiling of arches are generally angular implying removal of the lost rock by fracture rather than by erosion. Secondly, concentric undulations on side walls also testify to the arch creation by a mechanical process, mostly by a downward fracture propagation. Occasionally some undulations are formed as "hesitation lines" along layer boundaries (Fig. 6i). In others they are unrelated to such boundaries (Fig. 6c).

Occasionally, several structures representing various evolutionary stages, like niches, en echelon fractures, partial arches and full shape arches occur adjacent to each other on a single exfoliation surface (Fig. 3d). As exfoliation progresses inside into the rock and involves a series of parallel slices, the arches penetrate further into the rock repeating the fracture process on successive slices ultimately producing large arches like the Red Arch and the Angle Arch. See Bradley (1963) for more information on arches in the Colorado Plateau.

The development of arches to their various shapes and sizes is independent of adjacent faults, as no such structures have been seen to be associated with the arches.

Horizontal partings

A distinction between layer boundaries and horizontal joints (sheets) in sedimentary rocks is not simple, because these two partings often look alike. In the Paris Basin, for instance, some partings in chalks cannot be categorized as either layer boundaries or horizontal fractures. However, occasional marl beds which alternate with the chalk layers help in defining the layer boundaries. Sheets are recognized when they cut fracture markings on earlier vertical joints (Bahat, 1991a, p. 265). The investigator of fracture also faces such difficulties in ZNP. We present

here two examples of horizontal parting which probably represent horizontal fracture rather than layer boundaries.

The first example (Fig. 6h) demonstrates via the analysis of fracture surface morphology the role of a horizontal fracture arresting a later vertical one. This horizontal parting is not considered to be a layer boundary because in other locations layer boundaries do not arrest undulations (Fig. 6g). A second example is represented by a group of large slabs produced by joints inclined at a dip greater than 45° . They cut a series of layer boundaries but arrest at a horizontal sheet (Fig. 3b).

Results obtained at the Yosemite National Park

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Tectonofractography

Incipient fractures in granite are recognized as groups of radial striae which mark various parts of the rock. In a completed form, incipient fracture is comprised of an origin, radial striae spreading out, and a concentric undulation, or a series of concentric undulations situated opposite the origin. The undulations form orthogonal relationship with the striae at their contacts, together producing a fan. On El Capitan N 32° E oriented cliff, distorted and partial fans are more common than completed ones (Fig. 9a-c). The size of a fan varies from several meters to several tens of meters. Also, the orientation of the fans varies. Some fans spread their striae downward from an origin at a high elevation, whereas, in other fans the striae spread sidewise or upward. On the granite cliff incipient fractures of the fan type are more common than the ICF identified in ZNP. Many neighboring distorted fans interacting with each other develop into large vertical exfoliation joints, several hundreds meters in size, while cutting countryrock and dikes without apparent change in direction. A few such exfoliation joints can be identified parallel to each other, producing series of slices one internal to the other with respect to the face of the cliff. On a two - dimensional picture it looks as if the cliff consists of

Figure 9.a.

Figure 9. Exfoliating joints in granites in Yosemite National Park.
a. A cliff on El Capitan striking $N 032^{\circ} E$, with a frame indicating an area which is further detailed in b.

Figure 9.c. Diagram of b showing multiple groups of radial striae in various orientations. Many groups occur in association with concentric undulations together forming distorted incipient fan fractures.

Figure 9.b. A close up photograph of incipient fractures on exfoliation joints in the frame outlined in Fig. 9.a.

disoriented exfoliation fractures meeting each other along irregular boundaries. A close - up view however, reveals a three dimensional structure. Letters A-D in figure 9c appear twice on a series of "shingles" representing the same slices with a missing portion in the center. Exfoliated slices detach from the cliff in a gradual gravity driven process, as revealed by certain undetached parts from the cliff (see dash line in figure 9c). Consequently, rock removal by erosion crosses exfoliations. This is different from ZNP where erosion is more confined to individual exfoliated slices.

Exfoliation fractures often conceal more than they reveal. An exfoliation joint striking N 27° E and dipping 42° NW on the south western side of the Half Dome (Fig.10a), reveals the approximate location of its fracture origin at the meeting area of the distorted radial striae (Fig.10b). Part of an external slice which had existed above this joint was removed, leaving behind a concentric rim of approximately uniform width of radial en echelons. Note that whereas merging of the striae occurs at the left side of the joint, the extrapolated merging of the en echelon segments on the removed slice would occur on its right side, implying opposite directions of fracture propagation in superposing exfoliation joints.

The concaved side of the en echelon rim on the remnant of the removed slice has quite a sharp boundary (resembling the en echelon rim of the Red Arch, see Figs. 8a and 10a, respectively), suggesting that the removed part had been a mirror plane. Measurement of the outcrop dimensions enabled the calculation of the en echelon rim radius r and the fracture stress, σ_f (using the procedure applied for the H.C.). For the r derivation two $2y$ distances (Fig.8d) were determined at different locations along the rim boundary, resulting in two r values differing 8% from each other, suggesting the error range. The values used for calculation were: $K_{IC} = 1.9 \text{ MPam}^{1/2}$ (average between 0.9 and 2.9 $\text{MPam}^{1/2}$, Atkinson, 1984), $E = 5.0 \times 10^{10} \text{ Pa}$

Fig. 10.a.

Fig. 10.b.

Figure 10. Exfoliation joints in granites at Yosemite National Park.

a. Photograph of a concentric rim of echelons at left representing a remnant of an exfoliation joint on a slice which has been removed.

b. Diagram of Fig. 10.a. The removal of the external slice exposed the surface of a second exfoliation joint whose origin is identified at P by the meeting area of radial striae.

(Segall and Pollard, 1983), $\gamma = 4.06 \text{ Jm}^{-2}$ for microcline (Atkinson and Avdis, 1980) and $\gamma = 0.69 \text{ Jm}^{-2}$ for Japanese granite (Atkinson and Meredith, 1987, after Muller, 1984). Accordingly, r was calculated to be 96.4 m. The result by the first method is $\sigma_f = 0.6 \text{ MPa}$. The two results by the second method using $\gamma = 4.06 \text{ Jm}^{-2}$ are 0.1 MPa and 0.4 MPa, and when using $\gamma = 0.69 \text{ Jm}^{-2}$ we obtained $\sigma_f = 0.1 \text{ MPa}$ and $\sigma_f = 0.2 \text{ MPa}$, see results before rounding in Table 1.

There is a resemblance between the results of σ_f obtained for the Red Arch in ZNP and for the joint SW of Half Dome in YNP. In both cases low σ_f values were determined when γ values for quartz and microcline were used, and close results were obtained by the two calculation methods ((0.5 MPa and 0.3 MPa (average between 0.2 and 0.4), and 0.5 MPa and 0.25 MPa, respectively, see Table 1)). Also, the en echelon rims of these two fractures are of the uniform width type (Figs. 8a and 10a). These correlations suggest similar fracture processes. Fracture surface energy data on granite are scarce and the γ for the Japanese granite is lower than that for microcline, giving lower results for σ_f , for which we have no explanation.

Three distinct exfoliation joints merging to a single fracture can be seen on a north cliff of Tenaya Lake (Fig. 10c). This fracture has been previously described and interpreted by Holman in a somewhat different manner (1976, p. 70). Joint A at the lower left side propagated from right toward left. Joint B started above joint A and propagated independently upwards towards the location where the two rappelling persons are sitting. Fracture C initiated in the circle and propagated upward and sidewise to the right. The little block D located between A and C does not have sufficiently clear markings to compel a connection between the two. Yet, the three joints merged into a single exfoliation fracture.

There is a distinction between a sub-horizontal sheet fracture and the steep slabs produced by exfoliation, which dip about 55° (Fig. 10d,e). Vertical streaks produced

Figure 10.c.

Figure 10.c. Three adjacent joints form together an exfoliation fracture. Note rapelling persons for scale. See text for further explanation.

Fig. 10.d.

Figure 10.d. Photograph of various fracture types on a slope of exfoliated dome, whose height is on the order of 250 meter from base of picture.

e. Diagram of 10.d. A horizontal sheet fracture (marked A), series of exfoliations in front view showing upward concaving niches at B. A series of slices deviating from verticality in profile at lower part of picture. Streaks that mark external slices (dash lines) do not mark internal ones at C. A large fan indicating fracture propagating upward towards right showing concentric undulations and striae orthogonal to them at D.

Fig. 10.e.

by dripping solutions cross the sheet fracture and several external slices, but they do not cross some internal slices, suggesting that some internal exfoliation fractures are younger than the sheet fracture and the more external exfoliations. Note an almost "completed fan" in figure 10e at D.

Arches

Arches are not as abundant at YNP as they are at ZNP. Dimensions of the Royal Arches (Fig.10f) are presented in figure 10g and in Table 2.

Sequence of exfoliation in the ZNP and the YNP by vertical streaks

Commonly, exfoliation fractures appear in series on a vertical wall. When a part of an external slice is removed, a more internal fracture surface in the exfoliation series is revealed. The criterion mentioned above of vertical color streaks, which develop on the fracture surfaces due to dripping solutions, has been repeatedly used in both YNP and ZNP. The streaks often mark the external slabs more than the internal ones, indicating that exfoliation occurred from the outside inward (Figs. 6e,f and 10d,e).

Figure 10.f. Photograph of the Royal Arches.

Figure 10.g. Diagram of the Royal Arches showing its measured dimensions.

Table 2: Measured parameters of arches in Zion National Park and Yosemite National Park.

	Red Arch Zion National Park	Angle Arch Zion National Park	Lady Mountain Zion National Park	Royal Arches Yosemite National Park
Strike	042°	334°	352°	277°
Dip	67° NW	87° NE	82° NE	64° SW
External large arch				
Height (m)	60			340
Width (m)	130			550
Internal (main*) arch				
Height (m)	56*	37*		100
Width (m)	86*	28*		250
Nich marked by radial striae				
Height (m)			6	
Width (m)			15	
Compounded arch and en echelon				
Height (m)			50	
Width (m)			20	
Elevation of base station**	4320	4402	4440	3970
Elevation above sea level***	4476	4512	4625	2775

** Approximately at the foot of measured cliff (feet).

*** At zero line of grids (feet).

Discussion

In discussing the fracture mechanism of an exfoliation surface, three basic questions arise: 1) the local stress distribution at the fracture incipience, 2) the reason for fracture circularity, and 3) the ubiquity of en echelon fractures to which many of the ICF grow, the stress conditions associated with this growth, and the reasons for different en echelon styles.

Stress distribution on ICF. The fracture markings on ICF, which include origin,

mirror, striae and undulations, basically imply dominance of mode I, resulting in tensile fracture and normality of the minimum compressive principal stress σ_3 to the exfoliation surface. Local deviations include superposition of mode III on mode I along the striae, and superposition of mode II on mode I along the undulations (Lawn and Wilshaw, 1975). The differences in shape of the ICF and the various orientations of the niches seem to suggest that the principal plane which contains the intermediate and maximum principal stresses, σ_2 and σ_1 , respectively, parallels the fracture surface, but σ_2 and σ_1 locally rotate. The large approximate circular fracture (Fig. 6e) implies approximately $\sigma_2 = \sigma_1$, whereas sub-horizontal ellipses (Fig. 6a) possibly suggest local $\sigma_2 \neq \sigma_1$. This description generally agrees with previous assessments of stress distribution on exfoliation joints (e.g. Cadman, 1969).

Exfoliation parallel to principal planes is not limited to flat planes. It also occurs locally, parallel to curved surfaces, when stresses permit (hence, the importance of this phenomenon along tubical structures like tunnels and boreholes).

Fracture circularity. We consider fracture circularity from two points of view: rock

mechanics (pore pressure) and fracture mechanics. Annular fracture markings somewhat resembling the above ICF often occur on subsidence and syntectonic joint

surfaces (Bahat,1991,pp.243,258).These markings describe circular fractures produced by pore pressure.The ICF in ZNP may also be the result of local pore pressure.Vertical streaks on cliff surfaces representing seepage of water at various outcrop elevations testify to ground water percolation in the rock (Gregory,1950). It suggests an early post uplift jointing by pore pressure.

Initial flaws ,such as elliptical cracks when exposed to critical stresses tend to grow to larger circular fractures.This is because the stress intensity factor is higher at the smaller dimension of the flaw and hence the velocity of fracture at this side is higher.This tends to increase the small dimension at a faster rate than the long dimension, resulting in the decrease of ellipticity (Irwin,1962).

One of the above mechanisms,or a combination of both may explain the common occurrence of ICF in the ZNP. Percolation of water through the granite is much more restricted, and hence, ICF in YNP are relatively rare.

There seems to be a greater accumulation of upward convexing crescent niches at high outcrop elevations (Fig. 7a,b) than upward concaving ones, and a greater concentration of upward concaving niches at lower elevations (Fig.3b).This problem however has not been studied statistically, and is left open for further investigation. If this observation is confirmed, it should justify the investigation of the hypothesis that high elevation fracture propagation was more intense upward, and at lower elevations fracture advanced more vigorously downward.

En echelon fracture. The exfoliation of an individual slice is locally, mostly a tensile process. En echelon fracture however is formed by a mixed mode operation (I and III). Sommer (1967, 1969) showed that en echelon cracking is enhanced and branching is suppressed by increasing the mode III/mode I ratio. On the other hand, a high mode I/mode III ratio encourages branching, and presumably hackling prior

to branching.

The ubiquity of series of parallel en echelon segments on exfoliated surfaces in ZNP may be the result of more than one mechanism. Two possible mechanisms are discussed below.

Sommer (1969) observed segmentation in AR glass at as little as 3.3° rotation of the parent fracture from normality to the tensile stress (or minimum principal compressive direction, in a more general case). If we assume that exfoliation occurs on surfaces which parallel σ_2 and σ_1 , such slight deviations of these surfaces from normality to σ_3 may be very common, and hence common occurrence of mixed modes I and III operations and ubiquity of en echelons. This generality is limited to geological environments under low compressional conditions (Bahat, 1991b).

The mechanism and criteria which determine the twist angle, produced between a parent joint and en echelon segments are not clear. En echelons maintain a single orientation on a straight joint even if the joint is marked by bilateral plumes, and the twist angle changes along a joint which curves along the strike. These suggest that remote stresses have a higher control on en echelon segmentation than local stresses. On the other hand, the twist angle seems also to be dependent on rock properties such as the angle of internal friction and certain boundary conditions (Bahat, 1991a, pp. 246, 179). This would fit an expectation of uniform twist angle in a rock regardless of orientation of the parent joint. A conclusion regarding the mechanism (or mechanisms) responsible for parallel en echelon segmentation in the ZNP should await further data on twist angles in these sandstones. Basically, exfoliation is the result of surface forces, modified by body forces.

Mirror planes surrounded by rims of radiating en echelon cracks are seen on a significant number of exfoliated joints in the ZNP. They also occur on fracture surfaces of technological materials. Hertzberg (1976, Fig.14.9) shows a mirror plane marked by radial striae that point to the location of fracture origin. The mirror is surrounded by a rim of en echelons. This result was obtained by a fatigue test on a steel turbine rotor (Yukawa et al. 1969). The fractographic calculations by Hertzberg indicate that the fatigue crack probably approached unstable conditions (involving abrupt increase in fracture velocity) during its late stages. The mirror plane investigated by Herzberg resembles mirror planes that we identified on exfoliation surfaces.

Better σ_f results are obtained for the H.C. mirror when the fracture surface energy value derived experimentally from quartz crystals is used. For the Red Arch mirror, on the other hand, results close to experimental data is reached when a γ value for sandstone rock is used. A comparison of the morphologies of these two mirrors shows two major differences. Firstly, the Red Arch mirror is much larger than the H.C. mirror. The other difference is in the properties of the rims. The rim of the Red Arch mirror consists of regular en echelon segments and it has a uniform width, whereas the rim of the H.C. mirror consists of rough en echelon hackles which display different lengths, resulting in non uniform width of the rim (Fig.8d).

What is the significance of this correlation? Following experimental results and the theory that the increase in mode I/mode III ratio enhances bifurcation and presumably hackling as well, and the increase in mode I/ mode III ratio increases en echelon development and suppresses hackling (Sommer, 1967,1969), it is suggested that the H.C. mirror was developed under conditions of higher mode I /mode III ratio than the mirror of the Red Arch. It correspondingly follows that the tensile fracture of the smaller mirror was more intense and rapid than that of the

larger one. The Red Arch mirror mostly fractured under slow fatigue conditions, although, unstable conditions could have been attained at late stages of the fracture, in analogy to the experiment by Yukawa et al. (1969) mentioned above. Following the general equation $K = \sigma \sqrt{C} \pi$ (Sih et al., 1962), under given stress, the stress intensity increases in proportion to the square root of the fracture-length, and beyond a certain length the fracture becomes unstable. This provides a theoretical basis for a joint to grow slowly up to a certain critical size as a smooth surface, beyond which new stress intensity conditions would alter the fracture surface morphology (see also Bahat, 1991a, p. 243). Note however, that both this generality and the analogy to Sommer's experiment on AR glass mentioned above, may be applied to geological environments only under conditions when compressional stresses are weak (Bahat, 1991a, p. 246). This is a situation that fits quite well exfoliation joints.

Accordingly, two explanations may be considered in search of accommodating above results. First, the higher σ_f required to rapidly fracture the H.C. joint, compared with the low fracture stress that was responsible for the fracture of the Red Arch mirror by a slower process fit the established fact that brittle materials attain failure under stresses considerably lower than nominal (under conditions of rapid fracture), when exposed to prolonged loading (Mould and Southwick, 1959; Sholz, 1972). This would explain the low σ_f values obtained for the Red Arch mirror by the second method when $\gamma = 2.54 \text{ Jm}^{-2}$ was used.

Alternatively, it is possible that rapid jointing of the H.C. mirror was intragranular (through the quartz grains), as indicated by the good agreement between the experimental and calculated results of σ_f for $\gamma = 2.54 \text{ Jm}^{-2}$. A good agreement on the other hand, is obtained for the Red Arch joint when the $\gamma = 88 \text{ Jm}^{-2}$ is used in the calculation, suggesting the possibility of an intergranular (around the quartz grains) fracture. Fatigue conditions enabled slow fracture propagation along grain boundaries.

These alternative explanations may be tested by exposing the Navajo sandstone to different tensile stresses at various load rates.

Distorted fans in YNP are made of radial striae and concentric undulations orthogonal to each other at their contacts, which imply contemporaneity. This morphology suggests sub - critical propagation rate below 4×10^{-5} m/s assuming dry conditions, and below 10^{-2} m/s if the fracture were immersed in water (Bahat, 1991a, p. 234).

Resemblance in σ_f results and in mirror rim properties of the fracture SW of Half Dome in YNP to those of the Red Arch in ZNP, suggest that early fatigue fracture that assumed high velocities during the late fracture stages, also characterized the fracture in granite SW of the Half Dome.

Morphological microstructure of a joint

The morphological microstructure of a joint may be viewed as a fracture aperture property. Fracture aperture relates to the nature of spaces and contacts along the interface, often determined by the population of asperities. The hydraulic behavior of joints depends on these properties. Fracture aperture also affects the fracture specific stiffness, which in turn influences the interaction of seismic waves (Bandis et al., 1983; Pyrak-Nolte et al., 1987). The fractographic findings of the present study demonstrate that spaces and contacts along exfoliation joints in sandstone and granite are not shapeless and random, rather, they often occur in specific patterns.

Take for example the undulations shown in figure 6g. During early stages of jointing, fracture markings on the two mating surfaces would complement each other in a closed fracture (Bahat, 1991a, Fig. 5.5, see present Fig. 11a). Normal separation (mode I operation) should result in an aperture with a uniform spacing (Fig. 11b). When combined modes I and II operate large anisotropic "tunnels" may develop (Fig. 11c). A combination of modes I and III on the other hand, would form

Figure 11.

Figure 11. Schematic sections of fracture aperture showing four morphological microstructures due to different matings of undulations along an exfoliation joint.

- a. Initial closed joint.
- b. Normal opening, by mode I operation.
- c. Deformation by combined modes I and II.
- d. Deformation by combined modes I and III.

a more compounded array of asperities (Fig.11d). Fracture stiffness is likely to be the highest in the section shown in figure 11a and is expected to be reduced to various extents in the other three sections. The importance of these microstructure properties as far as hydraulic behavior of the joint is concerned, generally increases with the decrease in aperture.

Canyon geomorphology in the ZNP

The walker along one of the NNW "hidden canyons" sees quite a different geomorphologic phenomenon from what is seen in the main canyon along the meanders of the Virgin River. Receding of the vertical walls along the narrow hidden canyons is basically limited to vertical exfoliation of the slices and their gradual detachment from the wall and collapse into the tributary floor. Other erosional elements play their role only when the tributary deviates from its controlling strike determined by the NNW prominent joints.

The development of the meanders of the main canyon on the other hand, is the sum of recedings due to exfoliation along NNW and NE directions parallel to prominent joints. Furthermore, also important is the detachment of thick slabs formed by prominent joints along their directions, particularly, the collapse of rectangular vertical blocks produced by the orthogonal architecture of the prominent joints. Sporadic erosion not along joint surfaces occurs as well.

Terminology of sheeting and exfoliation joints

Although sheets and exfoliation fractures form approximately by the same mechanisms, they seem to genetically and morphologically represent different categories. Returning to Gilbert (1904), who believed that sheeting was older than the topography, we can add, that exfoliation develops following topography. These would correspond, respectively, to uplift and post uplift fractures. Various authors (including Dale,1923; Cadman,1967 and Holzhausen,1989) made comments on

"generations" of sheet fractures (e.g. preglacial and postglacial). Similarly, Holman (1976) observed "hairline cracks, which are evident only where weathering has etched them into relief, commonly subdivide sheets into two to four secondary slabs". Hence, the term sheeting should be applied to horizontal and sub-horizontal fractures which maintain approximately uniform spacing with their neighbor (lower and upper) sheets, but generally increase their spacing with depth. Sheeting does not have to develop parallel to a previous fracture, although sheet fractures often occur in sets. Commensurate with the above, Holzhausen (1989) made the observation that "Sheet fractures must be products of states of stress that are approximately uniform over distances of at least tens to hundreds of meters in order to explain the regularity and size of the fractures". Exfoliation joints, on the other hand, are generated by fracture parallel to existing surfaces in all attitudes. They generally develop at short distances from the exposed surface (tens of centimeters), in low spacings, and produce rock slices of both uniform thickness and lenticular shape. Sheets and exfoliation joints reflect fracture propagation in principal planes normal to the minimum principal stress. In the latter slight deviations are fairly common.

Summary

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1. A dominant structural feature in the ZNP area is a N-NNW system of straight prominent vertical joints which cut hundreds of meters of the Navajo sandstone column and are hundreds of meters long. The azimuth spreading of these joints possibly suggests two sets: a major one and a set of minor importance. Narrow "Hidden canyons" spaced hundreds of meters apart and separated topographically from the main Zion canyon developed along joints of this system.

2. There is also an abundance of NE oriented prominent joints, but their azimuths are highly dispersed, and they are shorter. They developed orthogonal jointing with the N-NNW system, but did not produce "Hidden Canyons".

3. Exfoliation joints in ZNP and YNP mostly developed in series of parallel slices, where earlier slices developed at the rock surface. Subsequently, exfoliation proceeded inside into the rock.

4. Exfoliation surfaces are often marked by characteristic fracture morphologies which manifest initial stages in the development of these joints. In ZNP series of incipient circular and elliptical fractures, meters to tens of meters in diameter in the Navajo sandstone merged together to form larger joints, hundreds of meters across. Occasionally, radial striae on surfaces of incipient fractures point to the location of fracture origin. Less commonly, exfoliation developed along single wide fracture fronts, as revealed by series of undulations.

5. In YNP exfoliation in the granite initiated with many independent fractures having the shape of partial distorted fans meters to tens of meters in size. Each fan consisting of radial striae initiating at the fracture origin on one side and, often bounded by concentric undulation on the other. The growth of these fans in all directions and their merger resulted in large exfoliation joints hundreds of meters in size. A series of such vertical joints one behind the other builds the N 032° E cliff of El Capitan. In the granite, there are also less frequent large exfoliations that were developed by the propagation of single fracture fronts.

6. Two main en echelon styles are distinguishable. These are: series of parallel en echelons in uniform azimuth and spacing, and en echelons in radial segmentation. Special cases where radial en echelons occur in a rim that surrounds a fracture mirror plane enable the determination of the fracture stress. In ZNP the fracture stress of two joints was calculated. A comparison of the results with the morphologies of the en echelon rims brings to focus two rim types. The first type

has an approximately uniform width and regularly arranged segments, and the second type is with hackles of various lengths and shapes which are segmented in an echelon rim of non - uniform width. The former is thought to represent a fatigue fracture which attained high fracture velocity only towards late stage of the fracture, whereas the latter is an example of a rapid fracture. A rim of the first type was identified on a joint remnant SW of the Half Dome in YNP.

7. Arches are abundant in ZNP and less frequent in YNP. Their various shapes and sizes reveal their development to be closely associated with the exfoliation process. They developed into their arcuate shapes by failing mechanically along arcuate trajectories. No indications of arching association with neighboring faults has been observed in ZNP.

8. There seems to be good reasons to terminologically distinguish between the terms sheeting and exfoliation.

9. This investigation raises a number of questions that need to be further investigated:

- a. Establishing whether the N-NNW prominent joints in ZNP form a single set or two sets.
- b. Determine the intergranular versus transgranular fracture of Navajo sandstone by uniaxial tension applied at different load rates.
- c. Establish the approximate uniformity versus systematic change of the twist angle between the parent fracture and an echelon segments at different azimuths of parent fractures in a given rock.
- d. Find out more about the distribution and orientation of crescent niches on exfoliation joints.
- d. Study the detailed morphologies of fractures as they grow from grain boundary size to well defined fractographic entities, incipient circular fractures in sandstone and partial fans in granite, and distinguish conditions which promote fracture

propagation from many neighboring incipient fractures in preference to large fracture fronts.

- e. Characterize refraction of undulations and its dependence on rock properties.
- f. Investigate the physical relationships which determine the shape and pattern of en echelon rims surrounding fracture mirror planes.
- g. Expose the Navajo Sandstone to different tensile stresses at various load rates, and search for intergranular versus transgranular fracture.
- h. Study the effects of various morphological microstructures on fracture aperture.

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