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FRACTOGRAPHIC LOGGING FOR DETERMINATION OF PRE-CORE AND CORE-INDUCED FRACTURES -- NICHOLAS COMBS NO. 7239 WELL, HAZARD, KENTUCKY

FOSSIL ENERGY

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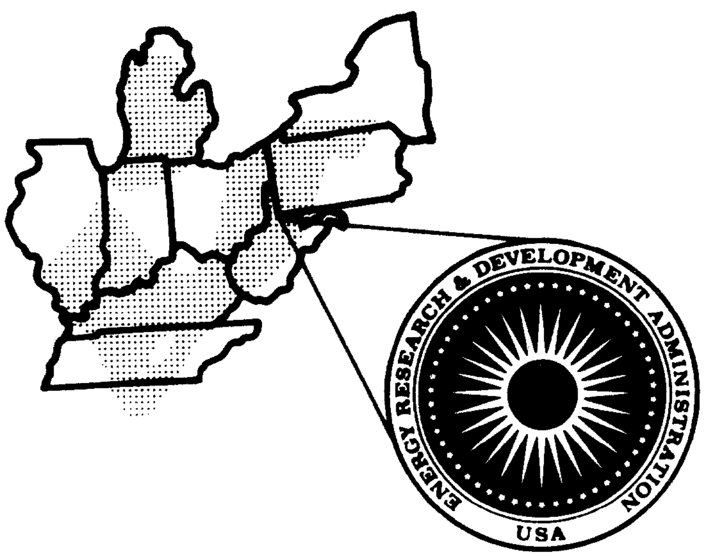
January 1977

EASTERN GAS SHALES PROJECT



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Report on Work Conducted
Under Contract ME6-P-2820
ERDA Morgantown Energy Research Center

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Fractographic Logging for Determination of Pre-Core and Core-Induced Fractures -- Nicholas Combs No. 7239 Well, Hazard, Kentucky

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Introduction and Purpose

This report is a summary of methods, results and conclusions formulated during a prototype fractographic logging study of seventy-five feet of oriented Devonian shale core. The core analyzed is from the Nicholas Combs No. 7239 well located twelve miles due north of Hazard, Kentucky (figure 1). The seventy-five foot core length analyzed in this report was taken from a cored section lying between 2369.0 feet (subsea) and 2708.0 feet (subsea). Total core length is 339.0 feet. The core was extracted from the upper Devonian Ohio and Olentangy shale formations (figure 2).

Perry County lines within the Appalachian Plateau. Here surface rocks consist for the most part of the Pennsylvanian age Breathitt formation. All rocks penetrated by the well are essentially horizontal.

All core samples were four inches in diameter with the exception of center-cored one and one-half inch samples used for experimentally induced fracturing.

The investigation worked toward three goals:

1) the development of a standardized procedure for a rapid and thorough core fracture logging technique;

2) the determination of which core fractures were present before coring and which fractures were induced during and after coring;

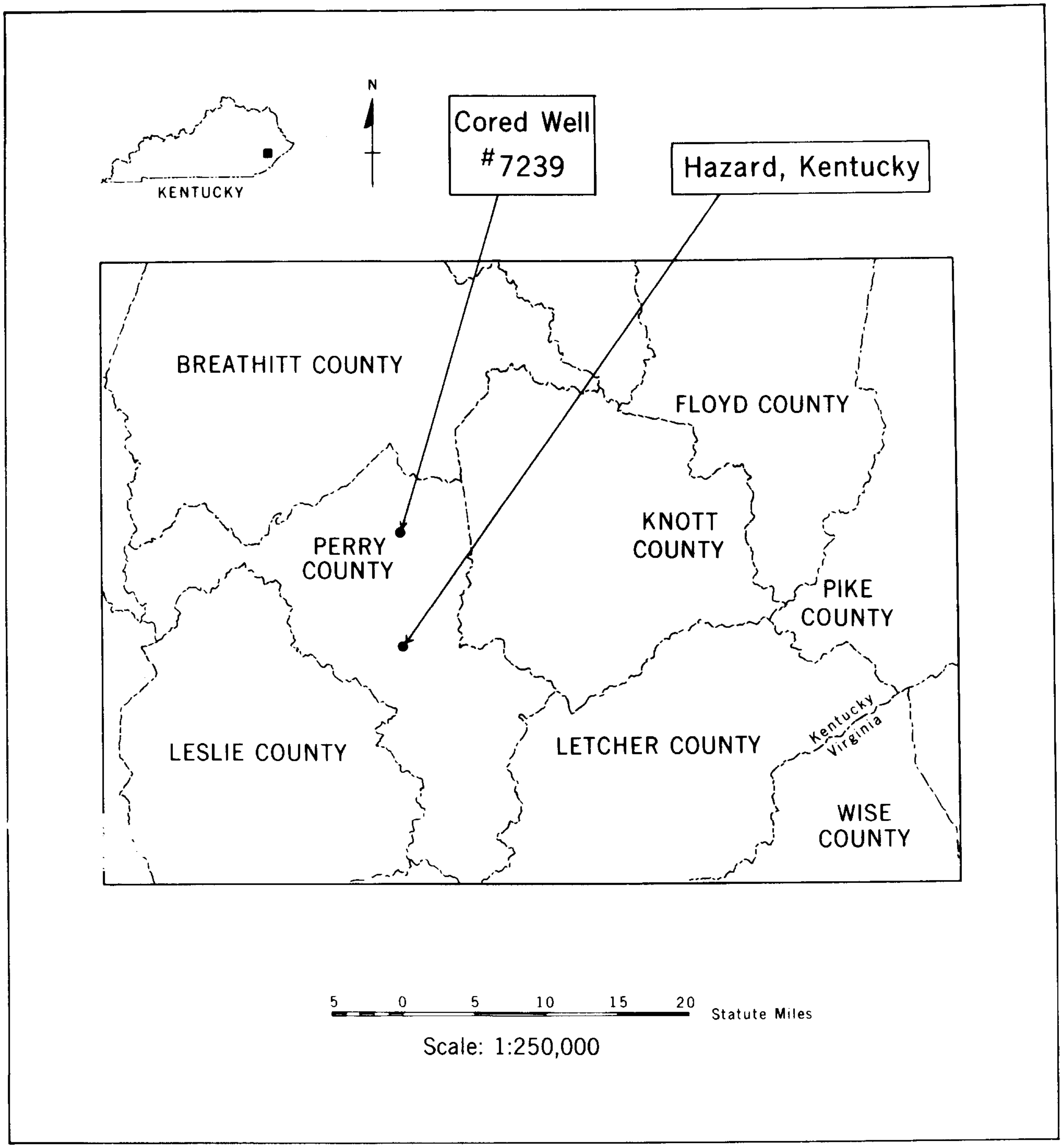

FIGURE 1 - Location of Cored Well No. 7239 in Perry County, Kentucky

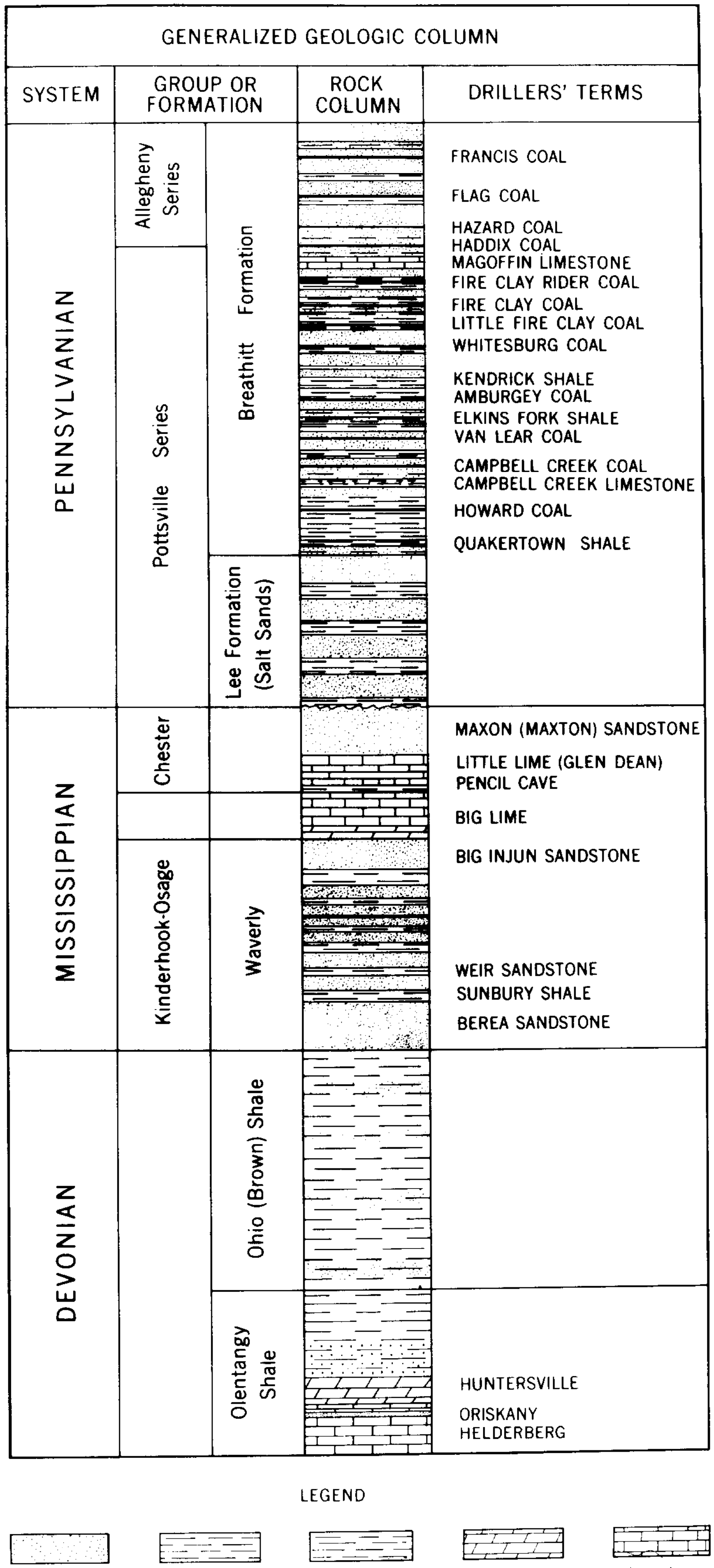

FIGURE 2 - Generalized Geologic Column for Cored Well No. 7239

3) the completion of an abbreviated but complete core fracture log containing fractographic study results of seventy-five feet of Devonian shale core.

The application of fractographic principles and processes constituted the integral part of the study. The utilization of fractography made it possible to distinguish core-induced or post-core fractures from pre-core tectonic or regional fractures that might serve as conduits for natural gas and oil migration. Without this distinction any attempt to deduce pre-core fracture patterns from core data is meaningless. In addition, after tectonic-induced (pre-core) and core-induced (post-core) fracture determination, the data from core-induced fractures might be used to gain some appreciation of stresses initiated within the core by drilling and core extraction procedures.

Various movement indicators on or contained within pre-core fracture surfaces and openings were also examined. Smooth surfaces, when slickensided, revealed pre-core slip directions. Fibrous secondary mineral growth within fractures given definite proof of pre-core fracture origin, and may also be utilized for interpreting principal paleo-stress directions active during fracture growth and mineralization.

Synopsis of Fracture Features Observed on Rocks

Fracture trace patterns and macroscopic-microscopic markings on fracture surfaces in any brittle or semibrittle substance (including rock cores) can be used to interpret fracture history. Information available from a fractographic analysis, if sufficient information is available, includes:

1) magnitude and direction of stress responsible for failure

2) the fracture origin location and the character of the flaw that served as the origin

3) fracture propagation direction

4) sequence of various fracture events

5) fracture velocities

A much more exhaustive treatment of principles and phenomena described in this section is available in: Frechette, V.D. (1972, 1973); Murgatroyd (1942); Poncelet, E.F. (1958, 1965); Preston, F.W. (1939); Pugh (1967); Shand (1967). Material presented in this abbreviated review is taken in part from these works and from the ongoing research of the present authors.

Any complete fracture surface leaves a readable record of the progression, from inception to conclusion, of that fracture event. Fracture development, always from a discrete origin, can be deciphered by studying the transient and tendential features associated with that fracture.

Transient features:

Transient features are short-range perturbations of a fracture surface. The resulting markings are often easily visible megascopically utilizing only reflected light. Some fracture face markings are so pronounced that they are easily visible on a large joint face from considerable distances. However, they can also be so subtle that their detection requires observation by optical means. On an extremely minute scale, the authors have even observed transient markings at a magnification of 3000X using a scanning electron microscope. Further, the reader can be assured that they exist on an even smaller scale than this. These markings at all scales record local perturbations in an advancing fracture front. The perturbations can be attributed to:

1) material inhomogeneities (fossils, pyrite nodules, pore space, etc.)

2) sonic wave interference

3) local changes in stress directions and stress gradients in the dominent stress field

4) fracture velocity variations

The subtle structures that arise from perturbations at the advancing fracture front are readily observed on the fracture surface of a fine grained material such as shale. Selected transient features commonly observed on rocks are described below.

Wallner lines

Wallner lines or ripple marks are subtle - low relief features that arise from the coupling of sonic wave displacement stress with the principal stress at the fracture front. These subtle lines are easily overprinted by more coarse transient markings, and are therefore rarely observed on the rough fracture surfaces of coarse grained polycrystalline rocks. A useful feature of Wallner lines, if they are evident, is that they are convex in the direction of fracture propagation. Wallner lines were not observed on core samples in this study; however, figure 3 depicts them in glass. Sonic waves responsible for the Wallner lines are generated when the fracture front passes by a flaw. The high velocity sonic waves thereby generated must catch up with the advancing, but slower moving, fracture front. Wallner lines form at the instant of interception by wave coupling. For this reason, the Wallner line is, in one respect, an imposter. It does not represent a true picture of the fracture front at a given instant. This is because the sonic wave does not overtake all parts of the fracture front at the same time. However, the curvilinear sections of Wallner lines will be convex in the fracture propagation direction. Sonic waves can also be generated by induced cyclic vibrations within the fracturing substances.

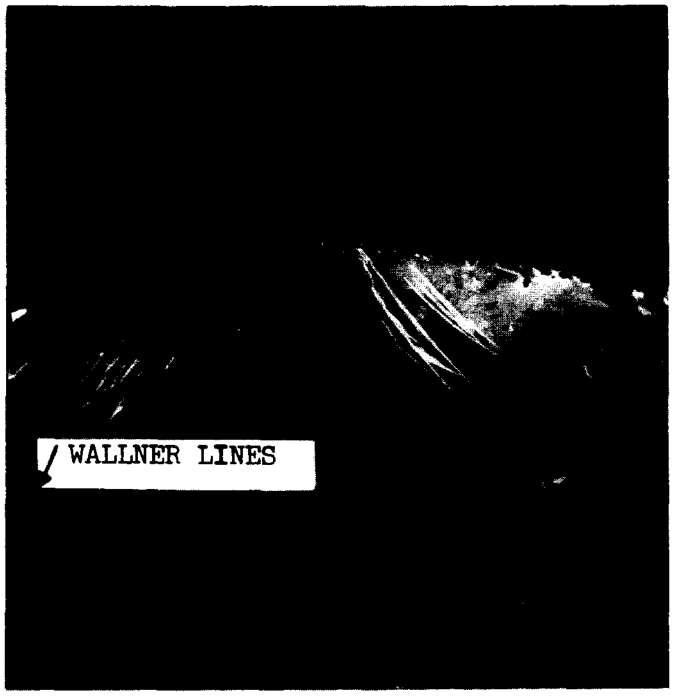

Figure 3, Wallner lines (ripple marks) on fractures surface of a glass rod. Concentric Wallner lines are convex in the fracture propagation direction and concave about the fracture origin located on the circumferential rod boundary. The photomicrograph was supplied by Dr. D. Lewis, N.Y.S. School of Ceramics at Alfred University (90X magnification)

Arrest Lines

Arrest lines or rib marks are generated through temporary fracture hesitation resulting from a momentarily decreased stress field or a sudden change in principal tension direction (figures 4, 5, 6, 7, 8). These features are significant because they record an instantaneous picture of the fracture front configuration at a particular point in time during fracture propagation. Arrest lines have been observed in glass, metals, rapidly cooled igneous rocks, lithographic limestone, rock salt, etc. The profile of an arrest line is a cusped wave. They are therefore more readily visible, in contrast to Wallner lines which generally possess less relief and are more rounded in cross-section. An interesting attribute of non-circular arrest lines that may be utilized in some fracture analyses is the fact that the advanced portion of the line can mark the area of maximum tension active when the fracture front passed through. The trailing edges mark the positions of less tension normal to the fracture propagation direction. However, this analysis cannot be applied to the circular arrest lines on set three fractures.

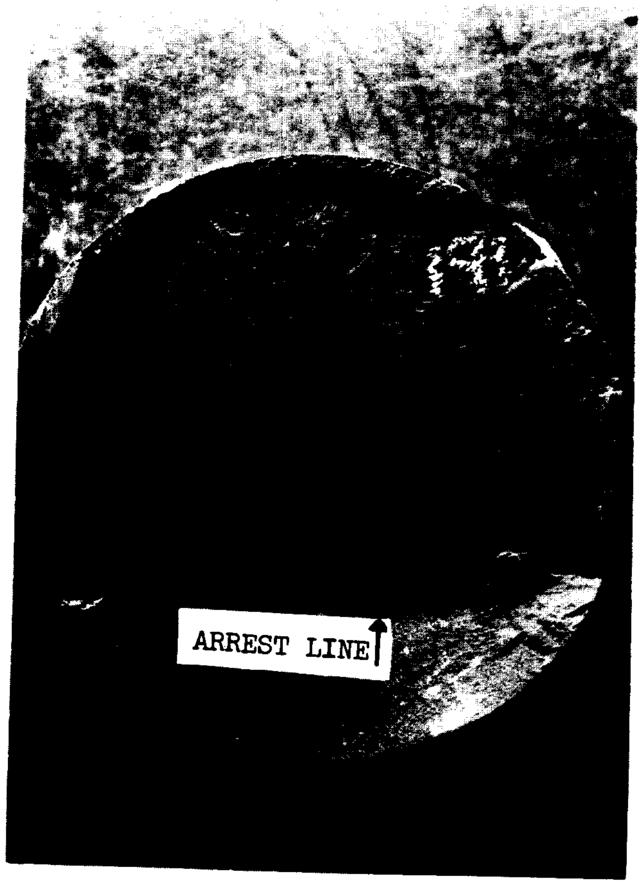

Figure 4, lingula brachiopod that acted as an origin flaw. Cohesion across the fossil face was very low or absent, causing stresses to peak at the fossil edges (fossil acted as an elliptical Griffith crack). Hackle plumes radiate from the origin to meet an arrest line and the core boundary orthogonally. Hooking occurs along sections of the circumferential core boundary. Note that hackle and an arrest line are continuous across the trace of an experimentally induced fracture.

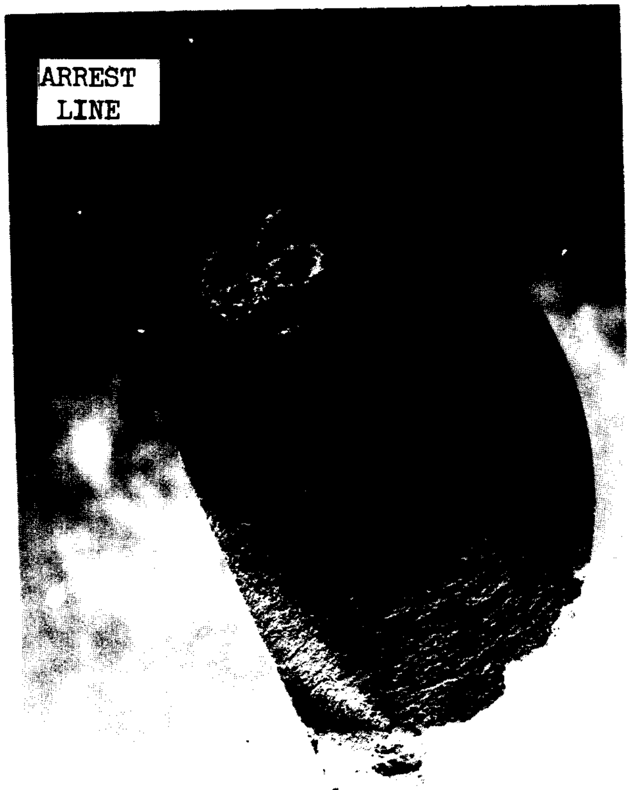

Figure 5, pelecypod that acted as an origin flaw. Cohesion across the fossil face was low or absent causing tensile stresses to peak at the fossil edges (fossil acted as an ellipsoidal Griffith crack). Hackle radiates from the origin curving to meet core boundary and earlier-formed vertical fracture orthogonally. Note arrest line also curves at boundary to maintain orthogonal relationship to hackle.

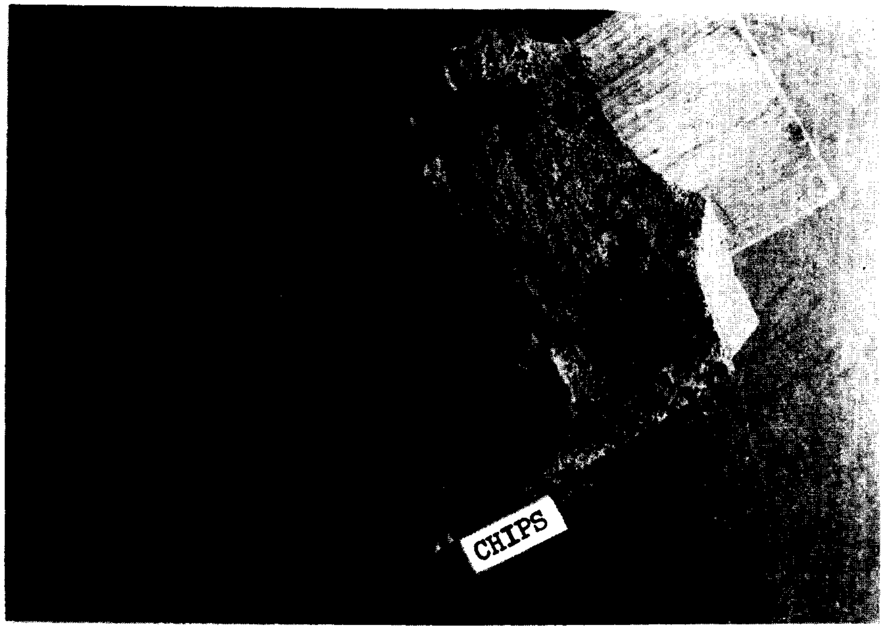

Figure 6, symmetrical arrest lines, convex downcore, and fine hackle and coarse twist hackle diverging downcore on a set three fracture surface. The fracture propagated in the direction of arrest line convexity. Note conchoidal chips preferentially located along right-hand core boundary fracture intersection.

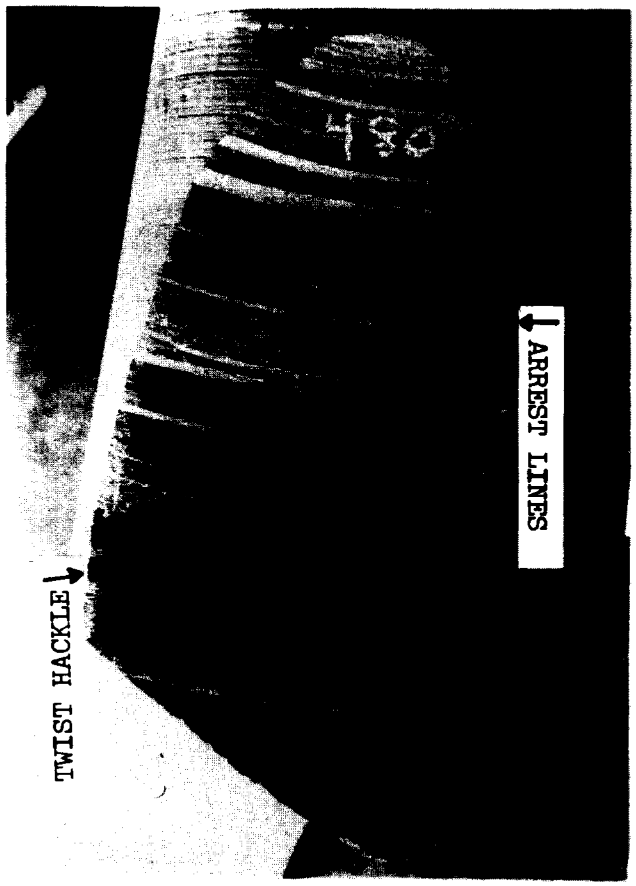

Figure 7, symmetrical arrest lines (note sharp ridges), convex downcore, and fine hackle-coarse twist hackle diverging downcore on set three fracture. Note twist hackle curving to meet the core boundary orthogonally.

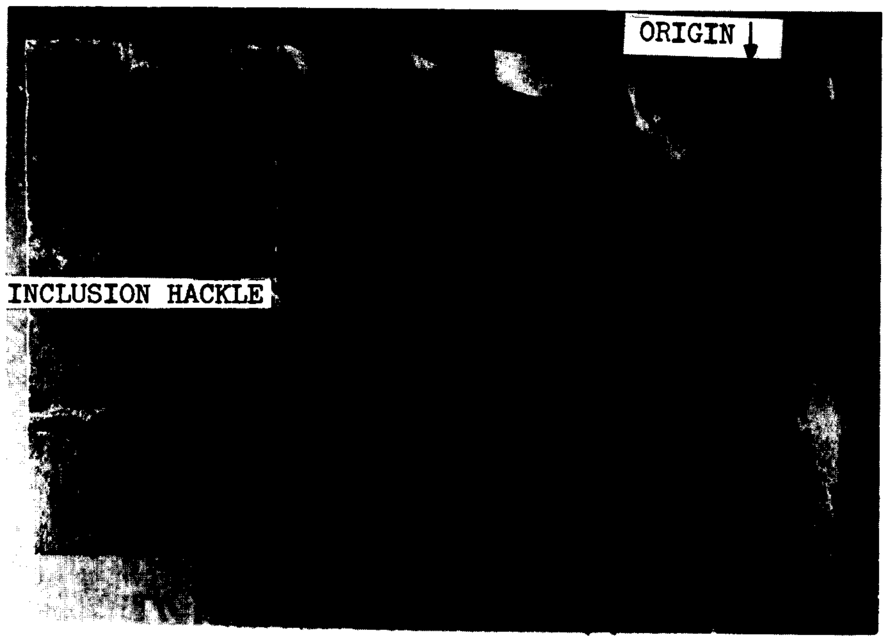

Figure 8, fracture origin at core boundary surrounded by circular arrest line. Twist hackle curves to meet orthogonally an earlier formed fracture surface immediately adjacent to the origin. Fine hackle spreads horizontally and radiates downward from origin. Note inclusion hackle generated when the fracture front encountered a pyritized bedding surface. Absence of arrest lines, the horizontal, earlier formed, fracture above the origin, and the origin location make this vertical fracture a rare exception to the majority of vertical set three fractures. It did not form during drilling and did not propagate vertically downward.

Velocity hackle

Velocity hackle results when a rapidly spreading fracture loses continuity along its leading edge. This occurs when the fracture velocity approaches sonic velocity of the material. The result is that adjacent parts of the front deviate again and again above and below the average plans of fracture as the fracture accelerates more rapidly at certain points than in adjacent areas. Later these advanced accelerated sections and lagging sections that then accelerate to catch up, each on a different plane, must interconnect to complete the fracture. This interconnection manifests itself as hackle steps and ridges that are parallel to the fracture propagation direction. These hackle ridges are usually short, discontinuous and chaotic in appearance. It is also often observed in rocks that all type hackle marks are orthogonal to arrest lines. Hackle marks generally diverge away from the fracture origin in the direction of fracture propagation. No investigation was made during this study to determine if velocity hackle exists on a microscopic scale. However, velocity hackle on a glass fracture surface is shown in figure 9.

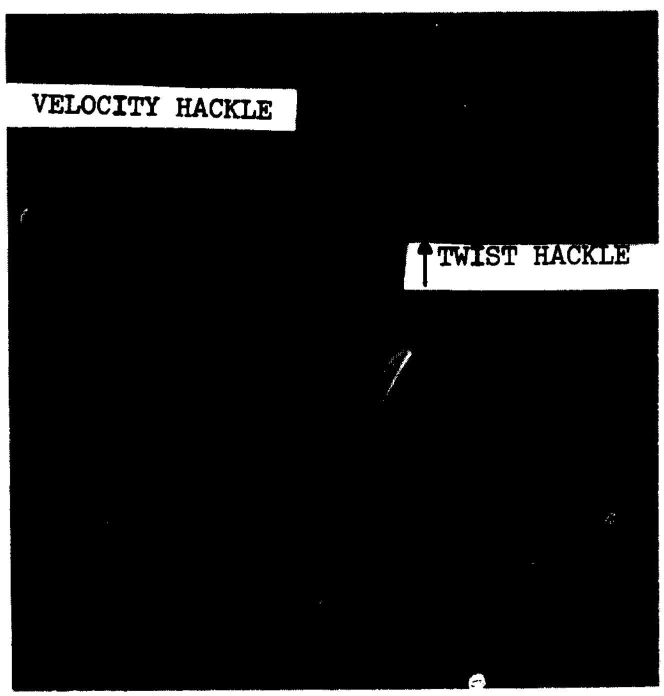

Figure 9, velocity hackle, chaotic and irregular on a fractured surface of a glass rod. Velocity hackle spreads from the bottom left to the top left half of the photo. Twist hackle diverges and spreads laterally to the right from the velocity hackle boundary at photo center. The photomicrograph was supplied by Dr. D. Lewis, N.Y.S. School of Ceramics at Alfred University. (1600X magnification)

Twist hackle

Twist hackle can be generated at fracture fronts, traveling at any velocity, when the direction of principal tension rotates in the plane containing the fracture front. The entire fracture front cannot respond by an instantaneous rotation to a new planar direction, perpendicular to the new principal tension, in a manner analogous to an airplane banking into a turn. Therefore, the fracture at the fracture front breaks up into individual en-echelon elongate tongues, each tongue inclined to the original fracture plane and perpendicular to the local resultant principal tension (much like the inclined blades of a half-opened Venetian blind). These tongues will continue to spread laterally and eventually curve into one another to complete the fracture, thereby producing the steps seen as hackle markings. In the field, coarse twist hackle is often observed at the boundaries of individual lithologic units exposed in fracture faces. In the core samples, twist hackle is commonly observed within the core interior, especially within regions where the radius of curvature at the fracture surface increases. Twist hackle is also formed as an advancing fracture approaches a pre-existing fracture or core boundary. Twist hackle is well-formed on some set three fractures, and is generally orthogonal to arrest lines. (figures 10, 11, 12, 13)

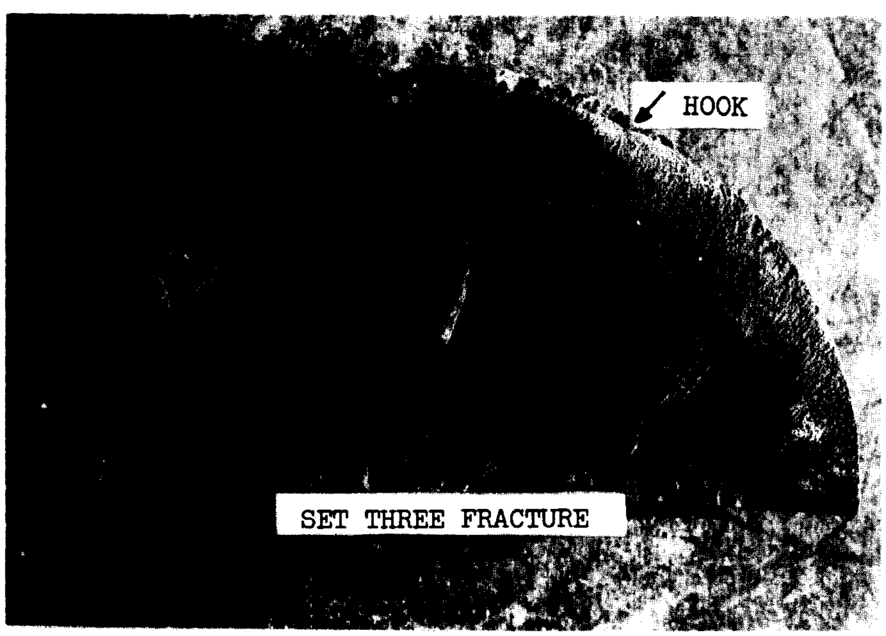

Figure 10, extended origin along earlier-formed set three fracture. Twist and fine hackle diverge to meet core boundary orthogonally. Note fracture hook at core boundary opposite set three fracture trace. At time of fracture, the core was in relative compression on the hook side.

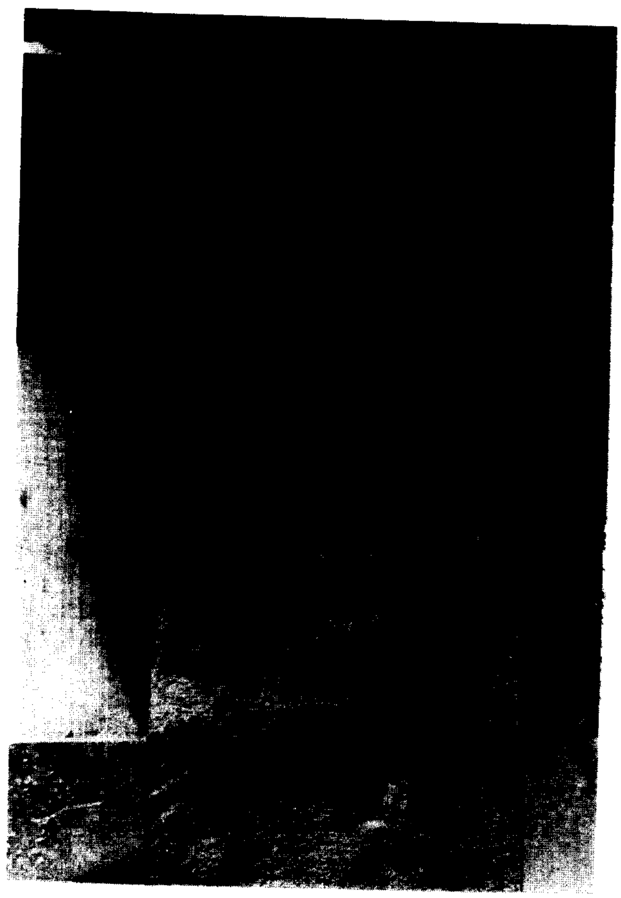

Figure 11, symmetrical arrest lines, convex downcore, and fine twist hackle diverging downcore toward the circumferential core boundary on a vertical set three fracture surface.

Figure 12, extended fracture origin along circumferential core boundary. Hackle radiates from the origin to meet the core boundary and earlier formed inclined fracture orthogonally. Note twist hackle forming near fracture boundaries. The fracture spread across the core, leading in the core center. The core center spreading direction was parallel to the inclined set three fracture strike direction.

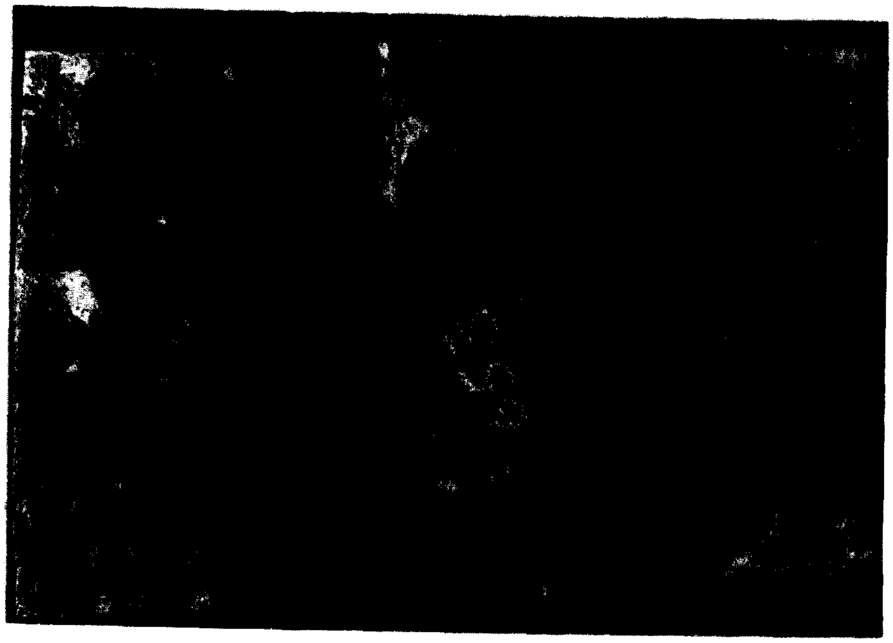

Figure 13, arrest lines convex downcore in fracture propagation direction, and twist hackle-fine hackle diverging symmetrically downcore toward core boundaries.

Inclusion hackle

Another type of hackle that may prove to be common in polycrystalline rocks cannot be attributed entirely to either excess velocity or a local superimposed stress direction. The term coined by the authors to identify this type hackle that is not created strictly by these two factors is "inclusion hackle." It is most likely generated in the following manner. When a fracture front advances into the vicinity of an inclusion (pore space, weakly cemented area, grain of different composition or size, etc.), the fracture plane can be locally warped by the interference of local stress gradients associated with the inclusion boundary. This planar warping, occurring as the main fracture plane passes around the inclusion, often results in the fracture being at different levels by the time it reaches the far-side of the inclusion (side opposite that first encountered by the fracture). The result of this divergence is, of course, that the fracture plane is not interconnected. Therefore, after passing the inclusion, the fracture should be advancing on two closely spaced sub-parallel levels. However, the fracture does not continue advancing indefinitely on two different closely spaced levels and soon rejoins to advance as a single front. In order to complete the break, the trailing fracture will step (hook up or down) into the other. This step forms a tail on the far side of the inclusion that points in the direction of fracture propagation (figures 8, 14). The term utilized throughout the report to identify this hackle step or ridge is inclusion hackle. The authors and V. D. Frechette (personal communication) predict that a microscopic inspection of hackle on granular rocks could prove inclusion hackle to be the dominant type observed on core fractures and on joint faces in the field.

All hackle types can be grouped under the term "plumose structures," transient features familiar to, but often poorly understood by, field geologists. During core logging, no distinction was made between the various hackle types unless a particular hackle form was exceptionally well-developed. If hackle was present it was generally recorded as fine or coarse hackle. Coarse hackle was easily visible and revealed the direction of fracture propagation.

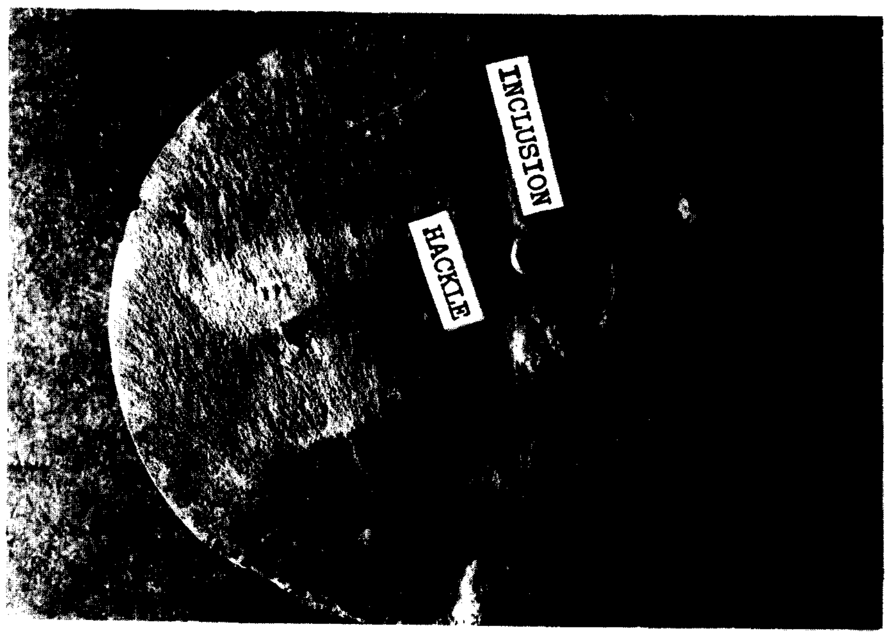

Figure 14, pyrite nodule near circumferential core boundary that served as an origin flaw. Hackle radiates straight across the fracture face through core center and curves to meet the core boundary orthogonally. Note inclusion hackle generated at pyrite nodule boundaries that face away from the origin ("lee side" of nodules).

Fracture origins

Fracture origins are the most important features in the discernment of the inception mechanics of a particular fracture. All fractures begin at an origin flaw, and the origin area is commonly marked by a dimple. This dimple is produced when the principal fracture curves in a very short distance from a plane containing the origin flaw into the plane perpendicular to the principal tension. Fracture origins in rocks commonly occur at fossils, vugs, concretions, flaws on bedding surfaces at previously existing fractures, etc. Origins on core-incuded fractures are located 1) at a scribe mark or flaw on the core boundary, 2) at a flaw on a previously existing fracture face, or 3) at a fossil or pyrite nodule within the core (figures 4, 10, 15, 16, 17).

Figure 15, pyrite nodule that served as an origin flaw. Hackle radiates from the origin and curves to meet the core boundary and earlier-formed inclined set three fracture intersection line orthogonally. Hackle pattern about the origin indicates that tensile stresses peaked at the inner core facing nodule boundary at time of fracture inception.

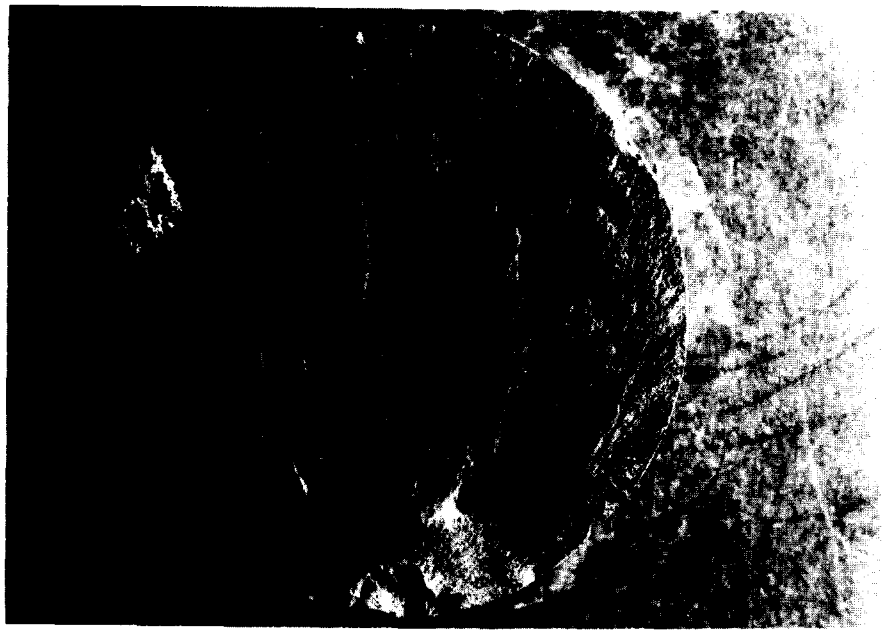

Figure 16, origin flaw at the circumferential core boundary. Hackle radiates from the origin and curves to meet the core boundary orthogonally.

Figure 17, fossil fragment that served as fracture origin flaw. Cohesion across the fossil was low, causing the tensile stresses to peak at the fossil edges (fossil acted as a very large rectangular Griffith crack). Note arrest lines, concave toward the origin, running through the core center. Fracture hooks into circumferential core boundary opposite origin. Hackle curves to meet the core boundary orthogonally.

Tendential features:

Tendential fracture features arise from long range changes in the stress field and are recorded as undulations in the fracture profile or trace (line formed by the intersection of the fracture plane and a previously existing free surface). The bifurcation (forking) or directional change in a fracture trace generally reflects long-range stress alterations rather than the local stress perturbations responsible for transient features. Tendential features generally proved to be of less overall value than transient markings in this particular core investigation.

Hooking

Hooking results when a fracture plane curves due to interaction with the neutral surface of a flexed object, or when a fracture plane curves in an attempt to meet a free surface orthogonally. Hooking proved to be helpful on certain occasions for determining fracture sequence in a particular core section. Later formed fractures may curve sharply, or hook as they approached earlier formed fractures (figures 4, 10, 18, 19). However, this interpretation must be applied with caution (figures 19, 31a, b).

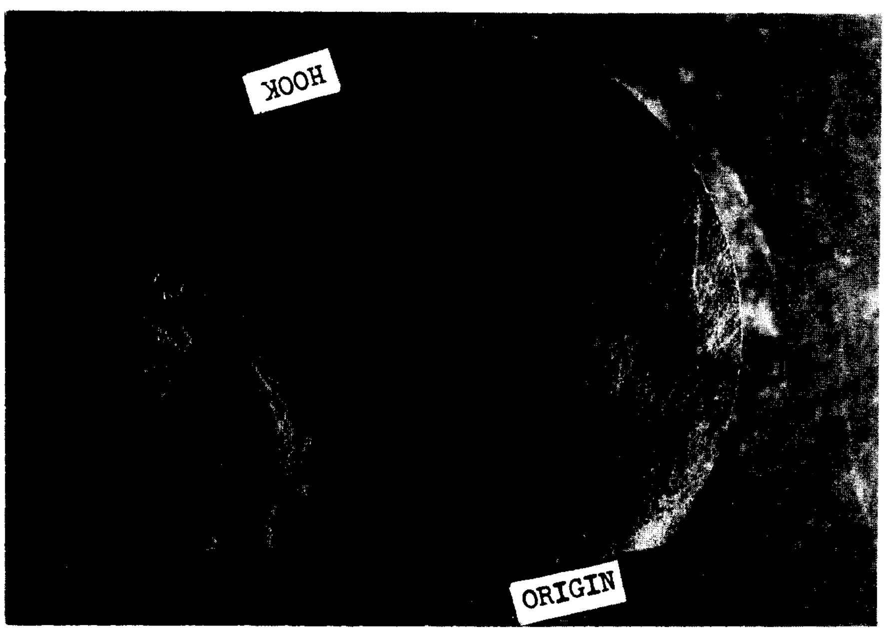

Figure 18, fracture origin at vertical set three fracture intersection. Hackle curves from origin to meet the core boundary orthogonally. The fracture plane undulates and hooks into the core boundary opposite the origin. Note twist hackle generated within the fracture hook.

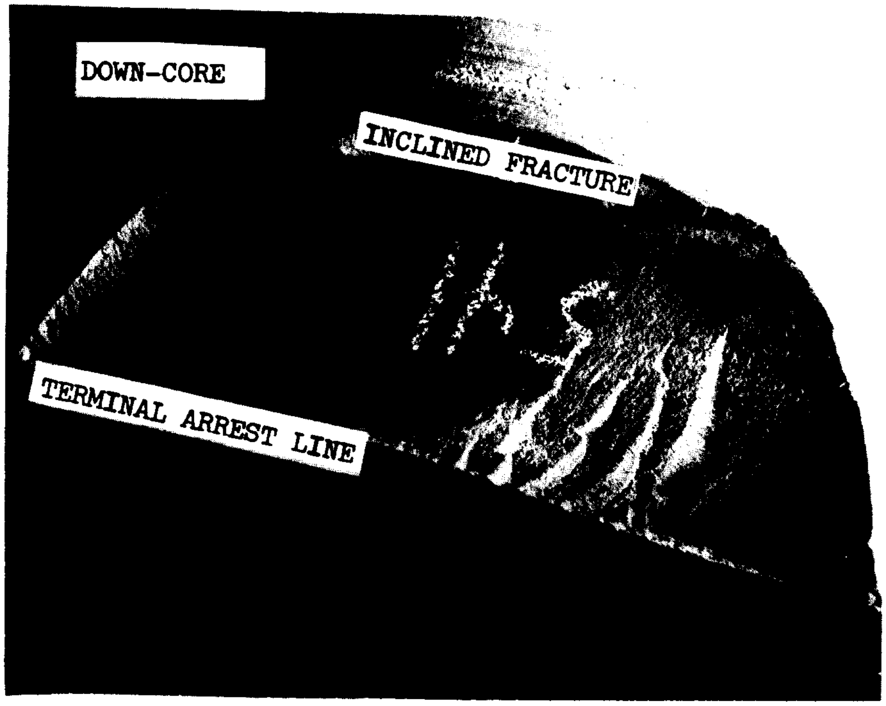

Figure 19, a regenerated vertical set three fracture. The terminal arrest line on the end of the vertical fracture face lies above the 541 mark. The trace of an inclined set three fracture hooks vertically downward into the inclined fracture. No arrest lines are visible on the joint fracture (541) indicating that it did not form during the drilling process.

Forking

The term "forking" is applied to fracture bifurcation into two or more diverging fracture planes. Forking is generated when a fracture reaches a limiting velocity in an increasing stress field. Forking can indicate fracture spreading direction because each forking segment diverges in the direction of propagation. The forking phenomenon proved to be of limited use in this particular study; however, it could be of great value in local or regional geological fracture investigations.

It should be emphasized that this fractographic summary is not an exhaustive treatment of the subject. For more detailed studies the reader is referred to the selected references. It should also be noted that several of the features described were only rarely observed on the examined core sections.

Determination of Core-Induced and Pre-Core Fractures

The identification of tectonically induced (pre-core) and core-induced fractures was determined on the basis of a number of observations on each examined core fracture. These observations included tectonic features observed on fracture faces, mineralized fibrous and nonfibrous fracture fillings, and the previously described fracture markings. The characteristics for determining tectonic-induced (pre-core) and core-induced fractures are tabulated separately below.

Pre-Core Fracture Characteristics:

1) Polished and slickensided fracture faces (almost always smooth and planar). Investigators should be cautioned, however, that polished surfaces on clay-rich bodies (shale) do not mandate high formational temperatures and pressures. It is common practice for potters to apply a high polish to unfired clay vessels entirely by hand at room temperature and pressure.

2) Fractures filled by fibrous or non-fibrous calcite mineralization.

3) Smooth fractures extending entirely across the core and against which later fractures usually terminate. Again, the blind application of this characteristic can lead to error. Later-formed fractures may cross pre-core fractures if the pre-core fractures are re-cemented by secondary mineral growth and/or rebonding of clay particles by surface charges. Also later-formed fractures (core-included) could abut earlier-formed core-induced fractures.

4) Inclined-vertical fracture faces displaying small, often conchoidal chips at the fracture-drilled core boundary intersection. The chips hook to meet the inclined fracture orthogonally. On steeply dipping fractures these are preferentially located along the right-hand edge of the fracture face at the core boundary (fracture face toward observer - downcore direction pointed down). Discretion is warranted, however, for if a fracture induced by drilling were to propagate downward immediately preceding the drill bit, the fracture would itself be subsequently cut by coring. The fracture would therefore possess conchoidal chips along its right-hand margin. However, the fracture would not be tectonic (figure 6).

Core-Induced Fracture Characteristics:

1) A fracture origin at the core boundary or within the core itself, it is highly unlikely that the drill would consistently capture the origins of pre-core tectonic fractures.

2) Hackle marks diverging and attempting to meet the core boundary or pre-existing fracture surface orthogonally.

3) Hackle marks becoming more coarse, the hackle steps increasing in relief in the immediate vicinity of the core boundary or pre-existing fracture surface.

4) Twist hackle originating near the core boundary or pre-existing fracture surface. This characteristic is only relied upon when used in conjunction with other characteristics.

5) Hackle plumes on sub-horizontal fractures that diverge from the central core area in a spiral pattern indicating a torque stress.

6) Closely spaced arrest lines on vertical and inclined fractures; arrest lines are convex downcore and symmetrical about an imaginary line down the fracture surface center.

7) Hackle marks on vertical or inclined fractures that diverge downcore symmetrically about an imaginary line down the fracture surface center.

8) Fractures that hook abruptly towards the core boundary or a pre-core fracture surface.

Core Logging Procedures

A logging procedure that facilitates a sufficiently rapid examination and recording of core fracture orientations and fractographic features has been developed. Equipment utilized during the study is listed below.

> Binocular microscope, hand lens, high wattage large and small (narrow beam) light sources, large flask of dilute copper sulphate, dropper bottle of dilute hydrochloric acid, metal ring marked in degrees to 360°, sand bucket the same diameter as the ring, inclinometer, yellow marking pencil, log sheet (figure 32).

It is convenient to first arrange in order, side by side on a long table, all of the core boxes containing rocks to be examined. Then each individual core sample within a given box is reconstituted into its proper place in that core section. Highly fragmented core sections can be taped with a strong transparent mending tape. The reconstructed core is then marked off into feet and tenths of feet. Each individual fracture can now be assigned a logging number. The number is written on the fracture face with a marking pencil, taking care not to obscure important transient markings. Fractures within each box are numbered in an upcore to downcore direction with each consecutive box being lower in the section. A single fracture that is separated, but continuous into a number of core sections is assigned the same number. All planar or semi-planar fractures large enough to permit an accurate orientation measurement are numbered. Center-cored specimens and slabbed four-inch cores, subjected to experimental fracturing, are assigned numberes followed by an upper case letter, for example 553 A. Occasionally in sequential numbering, a fracture is missed. This oversight is corrected by later assigning the slighted fracture a non-integer number. The number of core sections that can be reconstructed at the same time is limited by available work space.

After the core section has been marked into tenths of feet units, and the fractures to be studied have been numbered, each individual fracture is examined. First the orientation of the fracture face is measured and recorded. All fracture faces within 10° of horizontal (relative to the core axis) are recorded as approximately horizontal. The orientation of inclined fractures is measured by placing the core sample containing the fracture into the sand bucket with the core axis vertical (if the core was drilled vertically). The calibrated ring is then oriented on the lip of the bucket so that the north, south, east, west directions of the ring coincide with those of the core. The fracture strike or slickenside direction is then easily determined. The inclinometer can now be used to ascertain fracture dip or slickenside plunge.

After fracture orientation measurements are recorded, the transient fracture features can be examined. It is often possible to complete the fractographic examination without the use of a microscope. However, in all cases the success of the examination depends upon the proper arrangement of illumination and on the orientation of the fracture surface in the light. The most effective megascopic and microscopic examination procedure requires study by light reflected to the eye from a well-defined source at such an angle that slight local undulations on the fracture surface sufficiently disrupt the light reflection to cause these regions to appear dark against a bright field or bright against a dark field. One of the light sources should be small enough to be hand-held, if necessary, to facilitate flexibility in choice of conditions for optical or naked eye examination. In fact, both light source and specimen manipulation is frequently essential to facilitate interpretation of details. The harsh white light emitted by the high wattage bulbs that are used can be diffused by passing the light through a flask of dilute copper sulphate. After a thorough examination and notation of all transient and tendential fracture features, slickensides, mineralization, etc., a judgment is made determining whether a given fracture is core-induced (C.I.) or pre-core (tectonically induced, T.I.).

Prepared four inch diameter and center-cored one and one-half inch diameter core plugs that were fractured experimentally by point and directional loading machines were studied separately. These fractures are obviously post-core and are recorded as experimentally induced (E.I.).

It is often possible, after a number of consecutive fractures have been examined, to determine the sequence of fracturing within that particular core piece. The sequence is recorded under the column listed "noteworthy features." Also included within this column are any phenomena of particular importance, and features deemed suitable for later photography.

When the logging procedure for all core sections within a given box is completed, the samples are placed back in the box in proper order. The box is then returned to its original position on the table. It is important not to stack the boxes until the entire study is completed. A re-examination of certain fractures is often necessary and samples to be photographed must be extracted.

The procedure just described best fits the author's operation plan and facilities. However, the method is flexible and can be modified to any investigator's convenience.

Prominent Fracture Set Characteristics

Nearly all the fractures recorded within the selected core sections can be grouped by presence of mineralization, slickensides, orientation, and fractographic characteristics into the four fracture sets listed below (Table I).

TABLE I: MAJOR CORE FRACTURE SETS

Fracture Set	Fracture Orientation	Outstanding Fracture Set Characteristics
1	Approximately horizontal	Fibrous-nonfibrous $CaCO_3$ filling; slickensided; smooth planar fracture surface; separation parallel to bedding surface; tectonically induced
2	Approximately horizontal	Well-developed transient markings; planar to sub-planar, semi-smooth to rough fracture surfaces; core-induced
3	Strike maxima at N. 40° E. and N. 45° W. N. 10° W. Dip from 30° to vertical	Well-developed transient markings, arrest lines usually present; origin often vague or missing on sample; however, origin was in many cases in proximity of core boundary immediately off highest upcore point of fracture - likely obliterated by drilling; dips are almost always toward core center; core-induced.
4	Strike - complete range of values Dip - vertical	Experimentally induced by point and directional loading; fracture surfaces generally rough and non-planar; distinct origins; experimentally induced.

Set One Fractures:

Fractures in fracture set one are interspersed at irregular intervals throughout the core sections examined. They are horizontal, parallel to bedding, have an average frequency of one per one-half inch, are planar and smooth, and are mineralized or slickensided (figures 20, 21). Fibrous and non-fibrous calcite is the predominant mineral filling, forming bands up to one millimeter thick. Calcite fibers always grow perpendicular to the sub-horizontal fracture walls, indicating the direction of separation and principal tension to be vertical. This configuration implies the presence of abnormal fluid pressure within the shale at the time of crack inception and separation. Fine non-tectonic bedding partings filled with pyrite bands and clay partings resemble the tectonic mineralized fractures; each should be treated separately under the microscope. However, the procedure was not followed because of time limitations. Only a few of these veins in each grouping were tested.

Slickensided fracture surfaces proved to be another tectonic indicator. Slickenside orientations of set one fractures from four continuous core sections are shown in figure 22. Primary slickenside orientation directions change in fugure 22, B, C, and D (downcore) respectively from N. 30° W., to N.S., to N. 30° E. Slickensides related to thrust faulting in D. trend E.W. and plunge 60° W. to horizontal. These movement directions could indicate regional transport of lithified sediments eastward into the Rome Trough. However, one would think that a regional movement plan such as this would give rise to uniform slickenside directions throughout the column. Many of the slickensides could be due to local movements on the flanks of low amplitude short wavelength discontinuous shale folds, perhaps due to differential compaction. Inclined slickensides trending E.W. and plunging west are related to thrust faults of unknown displacement. All curved slickensides, symmetrical about the core center, are obviously caused by drilling.

Figure 20, a slickensided pre-core (tectonic) fracture. Slickensides trend straight across the core striking N. 30° W.

Figure 21, two sets of slickensides on a pre-core (tectonic) fracture slip surface. Slickensides trending N. 34° W. overprint those trending N. 3° E.

Set Two Fractures:

Set two fracture surfaces range from planar to subplanar and are semi-smooth to rough. Occasionally a single surface is made up of several chipped fracture surfaces making fractographic interpretation somewhat difficult (figure 23). However, on most surfaces the transient features are well-formed, greatly facilitating the fractographic study. Fracture origins are found both within the core interior and along the drilled circumferential core boundary - fracture intersection (figures 3, 16). The origin of these horizontal fractures can also occur along the line formed by the intersection of the horizontal fracture and an earlier-formed fracture. A set two fracture origin located at the circumferential surface is often associated with a noticeable flaw such as a scribe mark or deep skuff. Origins within the core are located at flaws consisting of fossils, pyrite nodules, mineralized worm burrows and voids. The boundaries of these flaws, if the core is stressed by cross-bending or torque, are points of stress concentration. Hackle marks diverge from these origin points regardless of location and almost invariably curve to meet the core boundary and pre-existing fracture surfaces orthogonally. Hackle steps often become greater in relief as hackle grows more coarse toward these pre-existing boundaries. Twist hackle is also formed at many of the fracture bounding surfaces. The described fracture origin locations, coupled with the relationship of transient markings to core boundaries, indicates that these fractures are

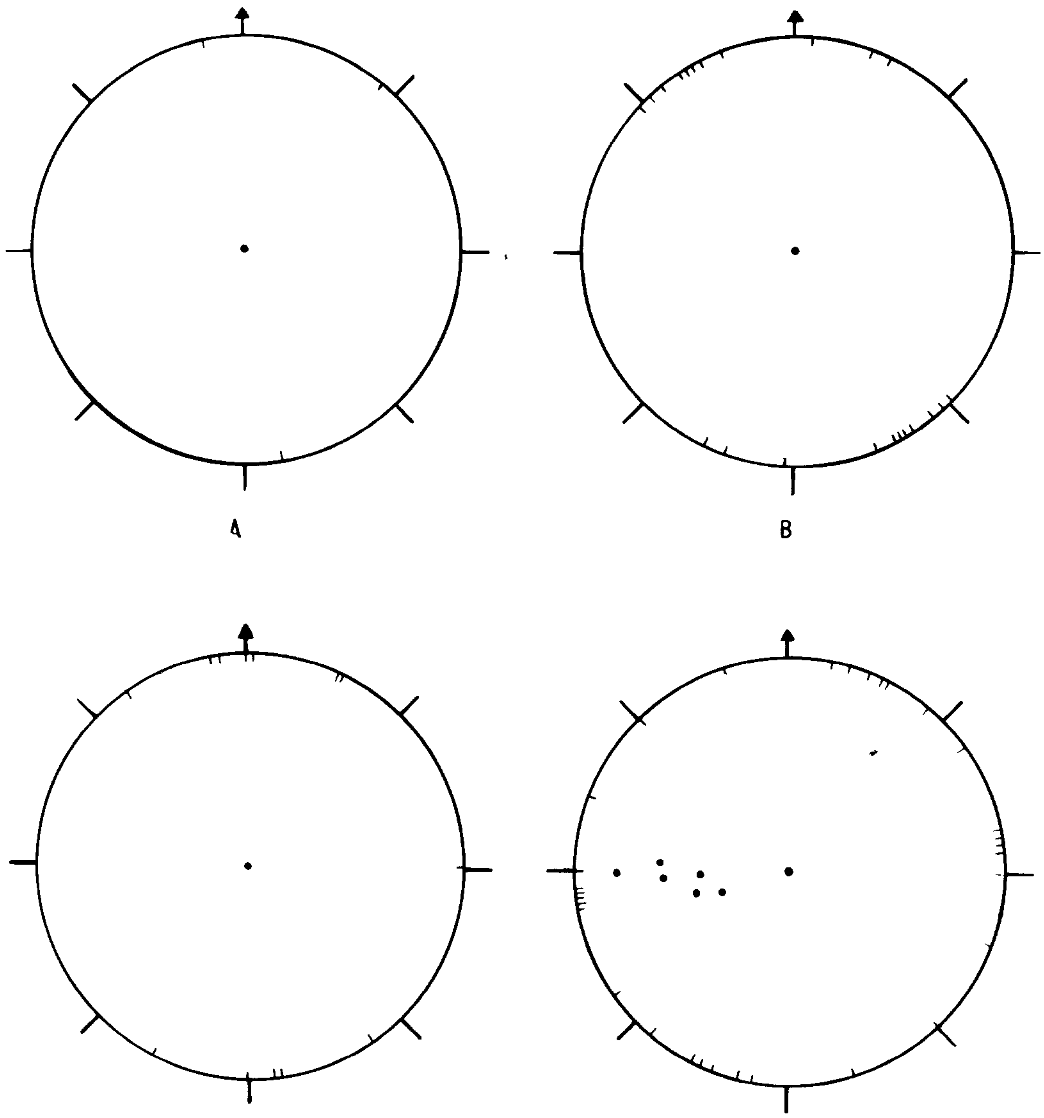

FIGURE 22, LOWER HEMISPHERE EQUAL-AREA POLE DIAGRAM SHOWING PLUNGE AND TREND OF SLICKENSIDES.

A) SLICKENSIDED SURFACE FROM 2373.85 FEET TO 2385.3 FEET
B) SLICKENSIDED SURFACE FROM 2407.58 FEET TO 2425.35 FEET
C) SLICKENSIDED SURFACE FROM 2588.8 FEET TO 2613.11 FEET
D) SLICKENSIDED SURFACE FROM 2633.58 FEET TO 2655.75 FEET

core-induced. Occasionally hackle plumes spiral from the fracture origin indicating a torque stress at time of failure (figures 24, 25).

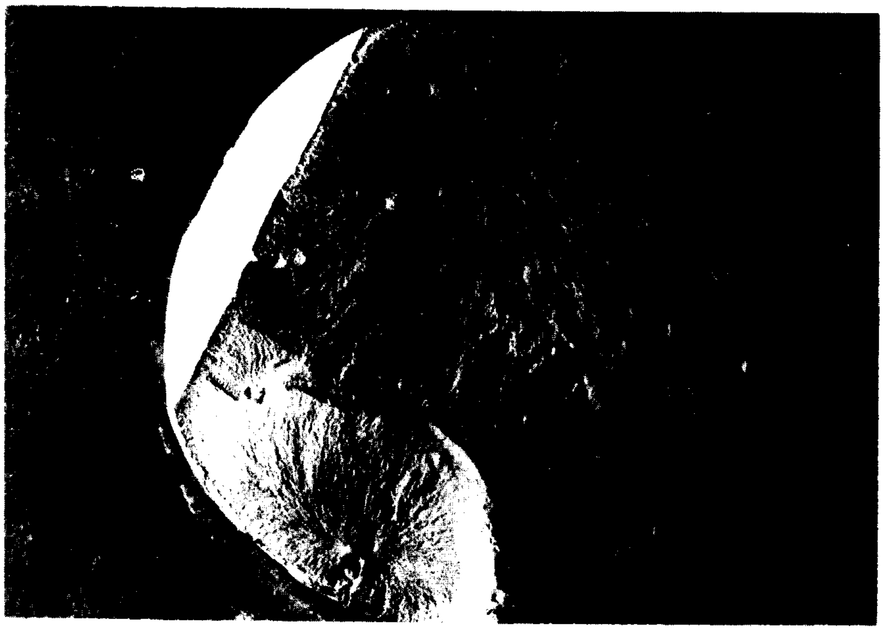

Figure 23, two distinct pyrite nodule origins on separate fracture chips forming a set two surface. Hackle radiates from both origins and curves to meet the core boundary and earlier formed set three fracture orthogonally. Note the discontinuity of hackle across the <u>fracture intersection</u> separating the two origins. The <u>intersection</u> line is concave toward the <u>second</u> formed fracture origin. Inclusion hackle from nodule to core boundary and hackle pattern about origin indicate that stresses peaked at the nodule edge facing the inner core at crack inception.

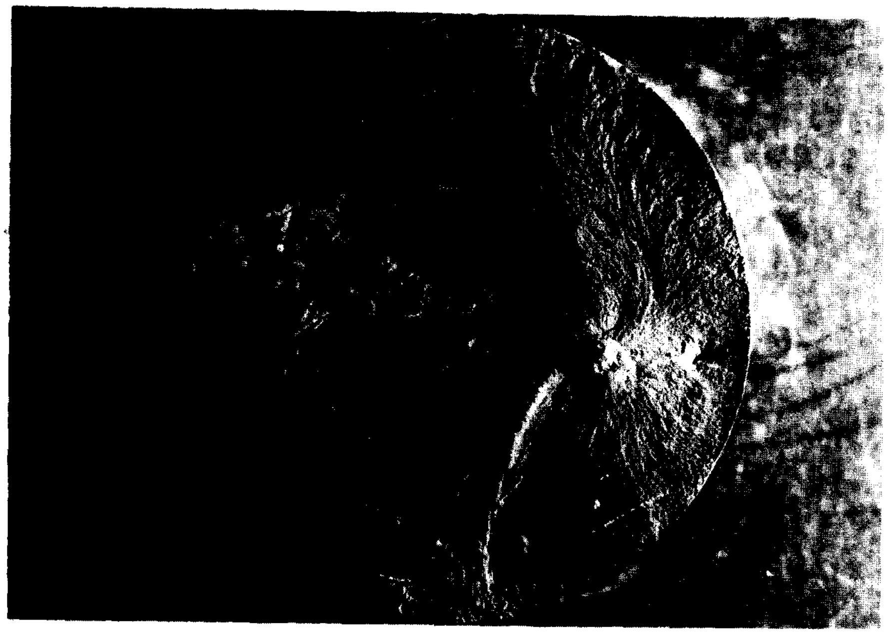

Figure 24, a fossil that acted as an origin flaw. Hackle on the horizontal fracture radiates from the origin and curves to meet the core boundary orthogonally. Spiral radiating pattern indicates a torque stress. Note the inclusion hackle spiraling from the edge of the fossil.

Figure 25, a pyrite nodule that acted as an origin flaw. Hackle on the horizontal set two fracture radiates from the origin and curves to meet the circumferential core boundary and earlier formed set three fracture orthogonally. Spiral pattern of the fracture indicates a torque stress.

Set Three Fractures:

Set three fractures have a strike concentration about three mean directions within four core levels (Figure 26, ABCD). Fracture dips are predominently toward the core center with dip values ranging from 30° to vertical.

Several inclined fractures did not belong in set three because of their slickensided surfaces or lack of symmetrical arrest lines and upcore to downcore fracture propagation direction (figures 8, 19, 27). The exclusion of these few fractures from the majority of set three surfaces serves as strong testimony supporting the potential of fractographic analysis in joint studies.

Set three fractures are generally smooth and planar to curviplanar; the fractures within this set, if continuous for any length (seldom over one foot), curve in a downcore direction to a vertical inclination while maintaining a constant strike (figures 6, 7, 13). Frequencies of four logged inclined fractures (less than 90° dip) per foot of core are not uncommon. However, only one vertical fracture section of any length exists within any given core section. This is logical since only one vertical fracture is necessary to relieve horizontal tensile stresses, and complete separation, in any given small volume of rock. No set three fractures are greater than four feet in length in any continuous core section, and no set three fracture cuts entirely across the core. These fractures simply cease to propagate downcore and terminate either within the core or at a set one tectonic fracture. Set three fractures can transect set one fractures if the latter are firmly cemented. Set three fractures may also curve outward toward the core boundary in a down-core direction to complete fracture separation. However, this occurrence is almost never the case, and the join completing the fracture separation is a later post-core event.

The exact origin is rarely discernible on these fractures; however, the origin area is always located near the uppermost (upcore) inclined section of the fracture plane in proximity to the core boundary. It is likely that many of these origins formed below the cutting edge of the drill bit and have been subsequently drilled away. The origin may rarely be associated with a scribe mark or skuff on the drilled core faces.

Closely spaced arrest lines (approximately three - four per centimeter megascopically) are common and are arranged in a symmetrical fashion about the fracture origin. The arrest lines are convex in a downcore direction and are symmetrical about an imaginary vertical fracture face center line. These arrest lines always lead downcore in the fracture face center. Cyclic variations in drill stem rotation and vibrations produced by drilling could have caused the tensile stress across the developing fracture plane to vary in direction and magnitude. This would cause the fracture to move forward in steps and produce the symmetry and uniform frequency of the arrests visible on the majority of set three fracture surfaces. These well-defined cusped features are not Wallner lines. Several sets of a symmetrical Wallner lines, convex downcore, and intersecting along the fracture center, would be evident if generated by sonic waves originating behind the fracture front at circumferential core boundary flaws (assuming they formed behind the bit). Also Wallner lines on a continuously advancing front, if due to

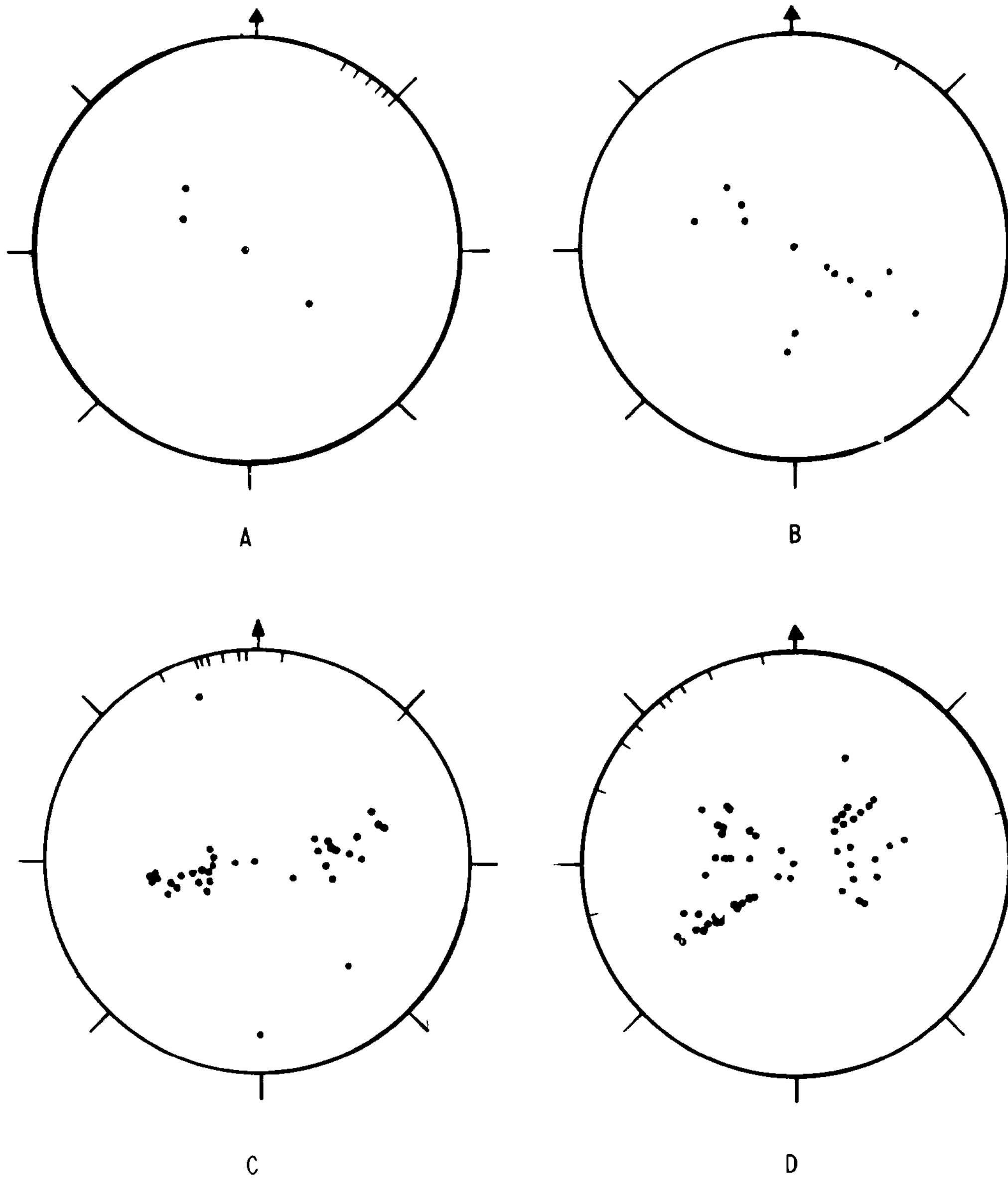

FIGURE 26, LOWER HEMISPHERE, EQUAL-AREA DIP LINE DIAGRAMS SHOWING SET THREE, CORE-INDUCED, FRACTURE ORIENTATIONS. TIC LINES AT THE NET BOUNDARY SHOW STRIKE DIRECTIONS OF VERTICAL FRACTURE. THE NUMBER OF TIC LINES EQUALS THE NUMBER OF POLES PLOTTED AT NET CENTER.

A) SET THREE FRACTURE ORIENTATIONS FROM 2373.15 FEET TO 2385.3 FEET
B) SET THREE FRACTURE ORIENTATIONS FROM 2407.58 FEET TO 2425.35 FEET
C) SET THREE FRACTURE ORIENTATIONS FROM 2588.8 FEET TO 2613.11 FEET
D) SET THREE FRACTURE ORIENTATIONS FROM 2633.58 FEET TO 2655.75 FEET

sonic vibrations, would not possess the observed constant radius of curvature (approximately six inches).

Hackle marks diverge downward symmetrically from the vertical fracture face center line, and maintain an orthogonal relationship to arrest lines. Twist hackle commonly become more coarse as they swing to meet the circumferential core boundary.

The vertical fracture faces can, in some core sections, be traced upward from their terminal arrest lines continuously through the inclined section to the core boundary and probable vicinity of the fracture origin. The transient and tendential features described show that set three fractures are core-induced. The closely spaced symmetrical arrest lines with a nearly constant radius of curvature, plus symmetrically diverging hackle that can meet the core boundary orthogonally, suggest set three fractures formed during coring. They could have formed in an already-drilled core section or at the cutting edge of the drill bit. A fracture originating below the bit's cutting edge could propagate vertically a short distance then cut diagonally downward into the yet-to-be-drilled area below the drill. The fracture would then swing to vertical again in order to remain perpendicular to the major horizontal principal tension. This option would enable the fracture to exist immediately before it was drilled, thus explaining the superposed chips concentrated on the fracture's right-hand edge caused by the later clockwise drill motion (figure 6). The lack of discrete origins, and hackle on these fractures not meeting the core boundary orthogonally, would also be explained. A fracture cutting away from the to-be-drilled area (if any) could not be observed. Arrest lines on many of these fractures indicate they did not propagate continuously, but grew in small increments above or below the bit. If these fractures spread downward before the drill, they would be present in the core hole wall. Any subsequent rubber impaction cast of the core hole could detect these fractures. They would, however, not be tectonic.

Mean set three fracture directions change downcore in figure 26, A,B,C,D. In diagram A and B, mean fracture strike is N. 40° E., dips vary from vertical to 30° N.W. and S.E. In diagram C, mean fracture strike is N. 10° W., dips vary from vertical to 30° N.E. and S.W. In diagram D, both above-mentioned sets are present plus a strong new fracture direction with a mean strike of N. 45° W., and dips varying from vertical to 30° N.E. and S.W.

In conclusion, almost all set three fractures are core-induced regardless of whether or not they formed above or below the drill bit. Most possessed symmetrical arrest lines indicating they formed during drilling. All true set three fractures possessed hackle that diverged symmetrically downcore. The few inclined or vertical fractures that do not fit into this category propagated horizontally (still with origin at core boundary) or were slickensided. Several vertical fractures possessing unusually smooth and planar fracture faces displayed only fine hackle that did not meet the core boundary orthogonally. Arrest lines were not observed on these faces. The largest ones of these trended in a N. 40° E. direction. There is a remote possibility that these may have existed before drilling. However, these fractures also propagated in an upcore to downcore direction. Several of these fractures cut diagonally into the core like many other set three fractures. The investigators are inclined to believe these fractures to be core-induced also.

Three mean strike directions for set three fractures at N. 40° E., N. 10° W., and N. 45° W., indicate that these fractures may follow some regional incipient fracture directions or poorly developed rock anisotropy. Also perhaps these fractures were influenced by non-hydrostatic stored strain energy released by drilling. This could be true regardless of whether the fractures formed above or below the drill bit. Further consideration of these possibilities necessitates an explanation for the downcore change in mean set three strike directions. Artificially induced fractures from thirty-two point loaded core samples taken from the examined section showed preferred breaking directions of N. 40° - 60° E., N. 0° - 10° E., N. 20° - 30° W., N. 50° - 80° W. These maxima are inconclusive, however, and do not prove whether a pre-fracture anisotropy exists.

Figure 27, inclined thrust fault slip plane, orientation N. 65° W., 40° N.E., slickensides plunge 25 N __ E. Vertical set three fracture cuts through recemented fault plane.

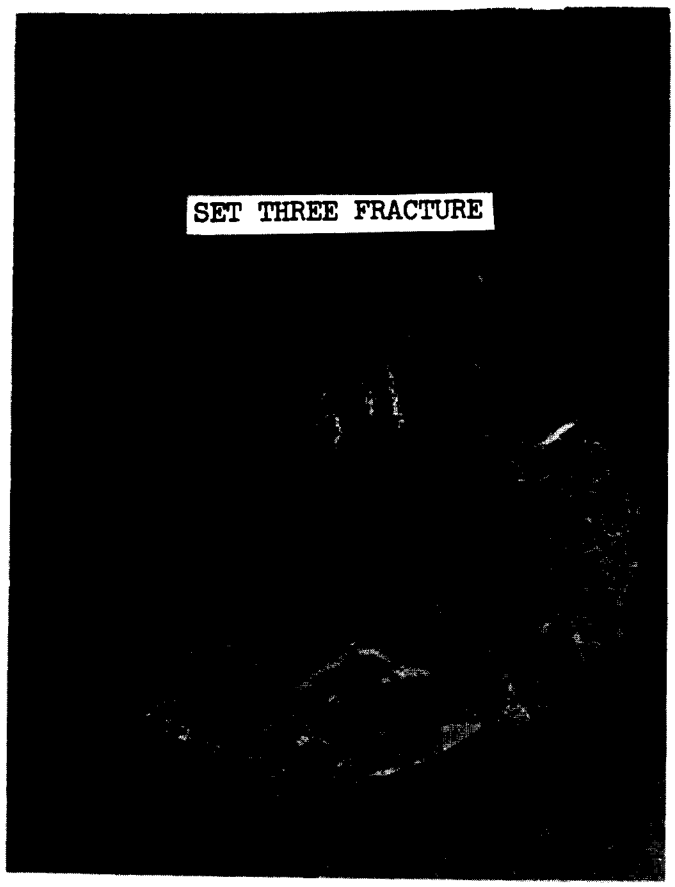

Figure 28, inclined set three fracture (tendential view) extending through recemented pre-core set one fracture. Tensile stress at the advancing set three crack tip was maintained across the re-cemented fracture.

Set Four Fractures:

Fracture set four contains all fractures experimentally induced by point and directional loading devices, in tests run by Energy Research and Development Administration personnel. These fractures are, with very few exceptions, essentially vertical. Strike diagrams for experimentally induced fractures are shown in figure 29. The fracture surfaces are often extremely rough and never smooth. Fracture strike direction is, for many samples, irregular. An averaged strike direction for these samples is measured. Fracture origins on point loaded core plugs are almost always at the point load contacts. Occasionally several fractures spread from these origins to split the sample into three pieces. Well-developed hackle on point loaded samples indicates these fractures spread into the core interior, then diverged sub-horizontally to the circumferential core boundary. Directionally loaded core samples also split vertically. Origins on these samples are, however, located on the circumferential boundary. The origin is often marked by a "powder zone" surrounded by fine hackle. These fractures spread horizontally to subhorizontally across the tested core sample.

No predominant induced fracture directions exist in experimentally fractured core samples (figure 29). Local fracture strike groupings evident in diagrams B and D at N. 60° W. and N. 30° W. are controlled by directional loading. There are weak preferred failure directions in point loaded core samples concentrated between N. 20° - 30° W., N. 50° - 80° W., and N. 40° - 60° E. - N. 0° - 10° E. However, no point loaded sample failed in a N. 45° W. direction as did many set three fractures.

Sequence of Fracturing

Set one tectonic fractures obviously existed throughout the drilled section long before coring operations began. Set three vertical and inclined fractures often abut against the horizontal slickensided surfaces of set one fractures. Set two sub-horizontal fractures may hook abruptly into set one fractures. Set two and three fractures have their unique configuration and geometry because the slickensided fractures served as free surfaces to prevent further propagation of stresses necessary for failure. However, when the tectonic fracture is recemented through secondary mineralization, tensile stress operative on a later-forming fracture is maintained enabling post-tectonic fractures to cut across tectonic set one bedding joints (figures 27, 28).

Set three fractures formed while the core was being drilled. The majority of these fractures originated at the cutting edge of the bit and spread downward. Vertical sections of set three fractures terminate at, and inclined sections hook abruptly into, the slickensided tectonic fractures. Coarse hackle is often generated on set three fractures at these intersections.

Set two fractures generally formed after drilling. Subhorizontal surfaces of this set seldom displayed symmetrical even spaced arrest lines about an outer core or inner core origin. Also, hackle spread to meet set three fracture surfaces orthogonally where these sets intersected. Set two fractures abut against, but never cut completely across, set three fractures.

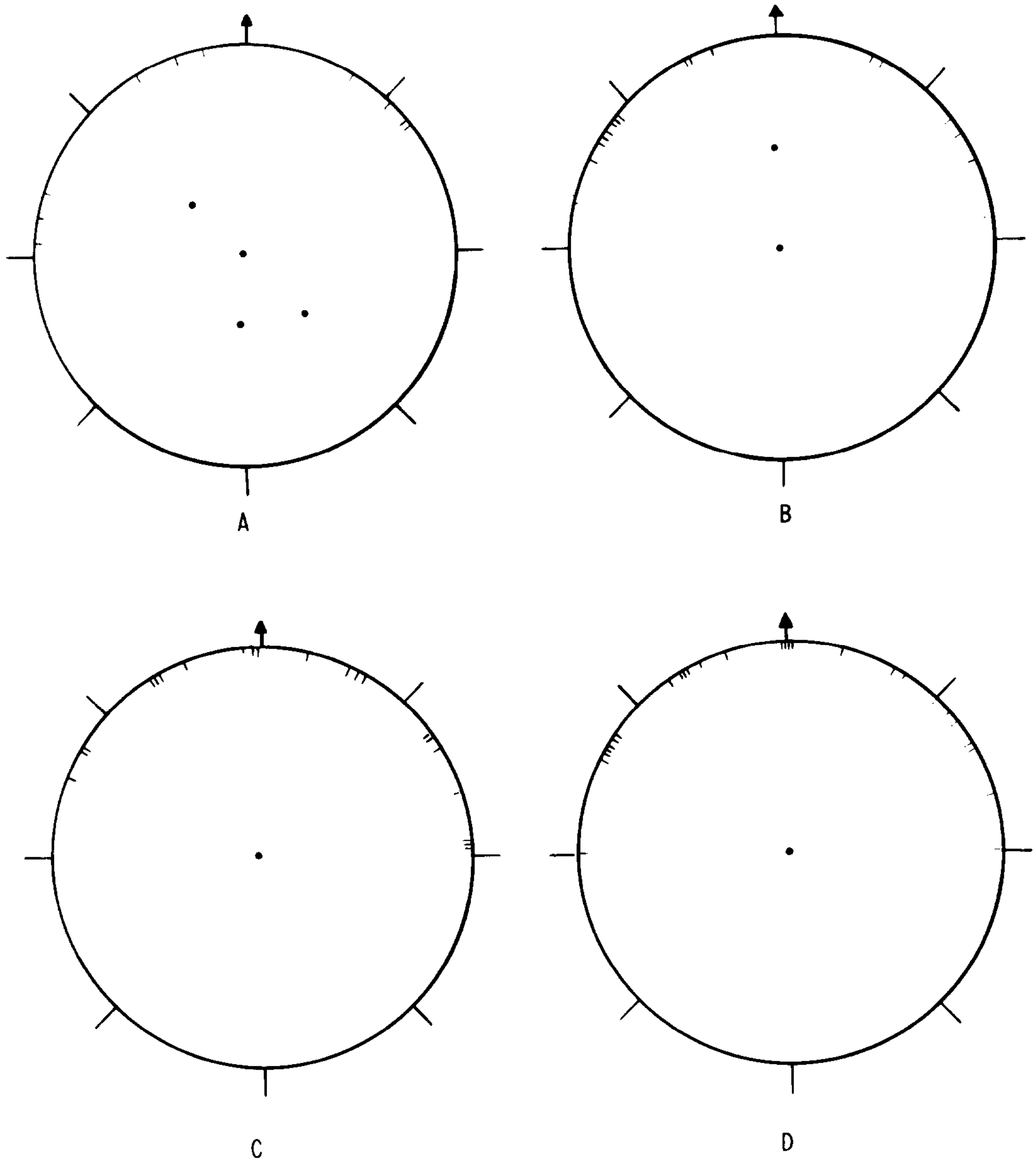

FIGURE 29, LOWER HEMISPHERE, EQUAL-AREA DIP LINE DIAGRAM FOR EXPERIMENTALLY INDUCED POINT AND DIRECTIONALLY LOADED FRACTURES. THE LINES AT THE NET BOUNDARY SHOW STRIKE DIRECTIONS OF VERTICAL FRACTURES. THE NUMBER OF THE LINES EQUALS THE NUMBER OF POLES PLOTTED AT THE NET CENTER.

A) EXPERIMENTALLY INDUCED FRACTURES FROM 2373.15 FEET TO 2385.3 FEET
B) EXPERIMENTALLY INDUCED FRACTURES FROM 2407.58 FEET TO 2425.35 FEET
C) EXPERIMENTALLY INDUCED FRACTURES FROM 2588.8 FEET TO 2613.11 FEET
D) EXPERIMENTALLY INDUCED FRACTURES FROM 2633.58 FEET TO 2655.75 FEET

Some set two fractures originated at the set two-set three fracture intersection (figures 4, 12, 25, 30, 31, 32).

This fracture sequence is maintained throughout the logged core section. Isolated fractures can be an exception to the overall sequence. However, few such exceptions are observed. The sequence of core-induced set three fractures obviously occurred in an up-core to down-core direction. Set two fractures, for the most part being post-core, could have formed at any location throughout the core during core extraction, center coring, other tests, and storage.

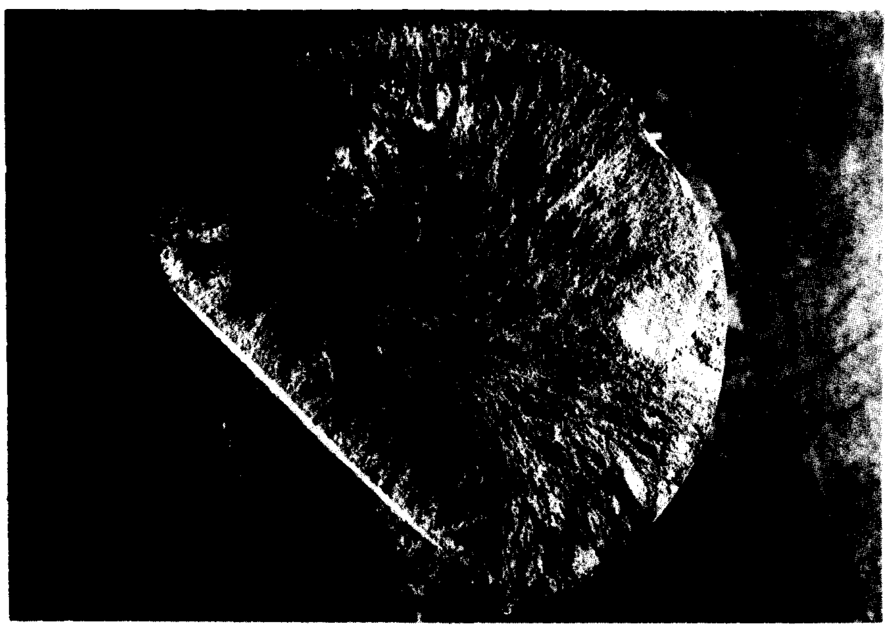

Figure 30, singular origin points on two set two fractures. Hackle plumes radiate from both origins to intersect an earlier-formed set three fracture and the core boundary orthogonally. The hackle pattern about the origin (large set two face) indicates that stresses peaked, and the fracture began, at the nodule boundary facing the core interior.

Figure 31, (a), tendential view of the apparent intersection of two set three fractures. The chalked lines highlight the fracture traces. Arrows point in the direction of fracture propagation. The fracture intersection gives the unfortunate impression that fracture 488 formed first.

Figure 31 (b), fracture abutting orthogonally against 488 separated from the core, thus exposing transient features. An absence of arrest lines on the fracture section curving to meet fracture 488 shows the join between the two surfaces did not form during drilling. Note the sharp terminal arrest line marking the boundary of the vertical fracture section. Therefore the vertical fracture formed first, the inclined fracture 488 formed second, and the breakthrough from the terminal vertical fracture arrest to the 488 interface formed last.

Conclusions

Study results indicate that a fractographic investigation is essential for any core sample logged for the detection of tectonic fractures. Without such an analysis any designation of the origin of a particular fracture is based primarily on the consistency of orientation and the relationship of the fracture to local and regional structure. This study has shown that consistent orientation itself is not an infallible criterion for the detection of tectonic fractures. The technique outlined in this report provides rapid and unambiguous identification of core-induced tectonic fractures.

All fractures logged in this study can be grouped into four fracture sets based on presence of mineralization, slickensides, orientation and fractographic characteristics. Two sets are sub-horizontal (set one, tectonic - set two, core-induced), one set is inclined from 40° to vertical (core-induced), and one set in experimentally induced by point and directional loading tests.

Our results indicate that there are few tectonic (pre-core) fractures within the studied core section. The region may nevertheless be cut at core sample depth by well-defined vertical or inclined tectonic fractures that the vertically drilled test core didn't intersect. This is quite likely since surface Plateau systematic fractures in other Plateau areas are vertical to sub-vertical and seldom have a frequency of less than one major fracture per foot. The remarkable directional preference of set three fractures about strikes of N. 40° E., N. 10° W, N. 45° W, suggests some incipient pre-core rock anisotropy or stored directional strain energy. If this situation exists, the anisotropy strike change or stored strain variance from N. 40° E. to N. 45° W. downcore remains an unanswered question.

Tectonic features, indicating local and/or regional movement plans, are present on and within the tectonic horizontal fracture set one. Slickensides had a preferred orientation within several core levels, and fibrous-non-fibrous calcite serves as fracture fillings.

Perhaps future Plateau cores, extracted for subsurface fractographic study, should be drilled inclined to bedding in some proper direction. However, before this conclusion is completely verified, additional Devonian shale cores should be critically examined. Pre-core fracture directions at depth, if discernible, should be compared to regional fracture directions for different lithologies determined at the surface.

All structural geologists are well aware that fractures (joints) are the most pervasive structures present in rocks at and near the surface. The authors believe that the principles of fractography, if properly applied, will prove to be a worthwhile approach for the kinematic and dynamic analysis of regional and local fracture patterns.

fracture number	foot	orientation	frequency	extent	origin	fractography markings	origin phenomena; opening direction	tectonic	noteworthy features

Figure 32, sample fractographic log sheet. In the actual log the following abbreviations are used: CI, core-induced; TI, tectonic-induced; EI, experimentally induced.

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