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ROLE OF FLUID PRESSURE IN JOINTING

DONALD T. SECOR, JR.

University of South Carolina, Columbia, South Carolina

ABSTRACT. Geologic evidence suggests that some joints are tension fractures developed perpendicular to the least principal stress direction in rock. In this study the mechanics of natural tension fracturing is examined in light of the fluid pressure theory developed by Hubbert and Rubey (1959). The Griffith theory of failure, expressed in terms of effective stresses, is taken as the failure criterion for rocks. In addition one of the total principal stress directions is assumed to be vertical and equal to the bulk weight of the overburden to the depth considered.

Calculations based on these assumptions indicate that tension fractures can develop at increasingly greater depth in the Earth as the ratio of fluid pressure to overburden weight approaches one. In particular, even a normal hydrostatic fluid pressure distribution will permit the development of tension fractures to a depth of several thousand feet, and as the ratio of fluid pressure to overburden weight approaches one, the maximum depth for tension fracturing becomes very great. The theory also indicates that previously formed fractures can be opened up by fluid pressure at great depth in the Earth's crust. Such open fractures probably are important in the migration of ground water, hydrocarbons, and ore fluids.

INTRODUCTION

Definition of terms.—In this paper the origin of joints is examined in light of recent theoretical and experimental advances in our knowledge on the role of pore fluids in the fracturing process. In order to accomplish this objective it is necessary to discuss the characteristics of both natural fractures in rocks and experimentally produced fractures in brittle materials. Through necessity two different sets of fracture terminology have evolved in geologic science. One set, used mainly by field geologists, is based on the apparent lateral displacement along the fracture, whereas the other set, used mainly by experimentalists, is based on the angular relationship between the fractures and the axes of the causative principal stresses. Unfortunately there is no general agreement on the precise meaning of terms, and so it is necessary to define the terminology used in this paper.

In order to discuss the mechanics of fracturing it is necessary to adopt a set of genetic terms for the different kinds of fractures. In experimental rock deformation studies the term *extension fracture* has been applied to fractures that form normal to the least principal stress direction (Griggs and Handin, 1960, p. 348). *Tension fractures* are a special kind of extension fracture that form normal to a tensile least principal stress. Conversely, *shear fractures* are inclined to the directions of principal stress and can occur in two conjugate sets, intersecting along the line of the intermediate principal stress direction, with the acute angle of intersection bisected by the direction of greatest principal stress. In the general case shear fractures have two stress components acting on the failure plane at the instant of rupture: a normal component (which can be either tensile or compressive) and a shear component. In one special case the normal component is zero, and only shear acts on the failure plane. The usage of the terms *extension fracture*, *tension fracture*, and *shear fracture* in this paper is in accordance with the above definitions.

In practical field geology it is undesirable to use a genetic classification for fractures because the stress history of a body of rock does not follow directly from observation of fracture patterns. In field studies the term *joint* is applied to fractures that have little or no tangential displacement, whereas the term *fault* is applied to fractures that have obvious tangential displacement (Billings, 1954, p. 106, 124; Beloussov, 1962, p. 136; Goguel, 1962, p. 56, 64; Hills, 1963, p. 150, 160; DeSitter, 1964, p. 99). In this connection the term "tangential displacement" is intended to mean an offset or movement parallel to the plane of the fracture. This dependence on an easily observed characteristic (that is, the apparent tangential displacement) in defining the terms joint and fault is necessary if the terms are to be useful and easily applicable in the field. In this paper the term *joint* will be applied to natural fractures that show little or no tangential displacement, whereas the term *fault* will be applied to fractures with obvious tangential displacement.

Field characteristics of joints.—Joints occur abundantly in almost all consolidated rocks now exposed at the Earth's surface. Indeed, with the possible exception of a few granite domes, this author is unaware of any sizeable mass of consolidated rock that is not jointed to some extent. Joints apparently begin to form in a rock mass as soon as it is capable of brittle fracture, whether the physical environment is that of weakly consolidated, geologically young near-surface sediments (Gilbert, 1882a,b) or deeply buried, metamorphic, metasomatic, or igneous rocks (Balk, 1937, p. 27-42) in which all previous fractures have been destroyed by melting, recrystallization, and plastic flowage. Curiously enough, jointing appears to reach its ultimate regularity and perfection in areas of near-horizontal sedimentary strata where other types of structural deformation are scarce or absent.

On the scale of a single outcrop one can usually recognize a few different sets of joint fractures that intersect without apparent offset. The fractures of a particular set vary somewhat in attitude and are spaced from a fraction of an inch to several yards apart. They extend laterally from a few inches to several hundred feet, eventually dying out and being replaced by other fractures of similar attitude in offset position. The fractures of a particular set typically exhibit a wide range in spacing and lateral extent, even within the limits of a single outcrop. In some places each bed has its own characteristic spacing of joints, and each joint is limited to a single bed. In other places the joints may slice through several beds of different lithology.

Close inspection of a fresh joint surface often reveals the presence of faint plumose markings becoming coarser near the fringe of the joint plane. These structures were first described by Woodworth (1895, 1896) in the Mystic River quarries near Sommerville, Massachusetts. Subsequently, Dale and Gregory (1911, p. 39), Parker (1942), Raggatt (1954), Hodgson (1961a, 1961b), and Roberts (1961) have described similar structures from a variety of places and environments. Hodgson and Roberts argue convincingly that the presence of plumose markings on a fracture surface indicates that there has been no significant lateral movement parallel to the fracture surface and that the center of convergence of the radiating markings indicates the point in the rock where the fracture originated. Roberts (1961, p. 489) also concluded that the markings originated from a rapid opening of the fracture in a direction normal to the fracture plane.

Regional studies have indicated that in many places the joint pattern is systematic over a broad area and through a considerable vertical extent of rock (Hodgson, 1961b; Parker, 1942). The joint pattern typically contains one or more double or conjugate sets consisting of two component fracture directions intersecting at 10° to 30°. At the present time it is not known whether most such conjugate sets are true intersecting shear fractures or whether they are two independent tension fracture sets which happen to intersect acutely. Orthogonal patterns are also particularly common. Joint patterns appear to be particularly well defined and systematic in regions of near-horizontal sedimentary rocks (Hodgson, 1961b; Parker, 1942). In both folded sedimentary rocks and metamorphic rocks and in basement terranes joints are more numerous and irregular, and careful analysis is needed to determine the joint pattern and its systematic variations (Spencer, 1959; Wise, 1964). In metamorphic terranes the initial joint pattern is often destroyed by flowage and recrystallization, and a new joint system develops in the waning stages of the deformation. In many places one or more of these new sets is about perpendicular to the structural trend (Christman and Secor, 1961; Turner and Weiss, 1963, p. 100-101). In igneous rocks joints can form during or shortly after cooling and may localize late stage alteration or may be reintruded by subsequent magma phases (Balk, 1937, p. 27-42).

The genetic relationship between joints and other types of structural features is uncertain. Apparently joints will always develop in consolidated rock even in the absence of other types of structural deformation. In some places jointing may be genetically related to folding or faulting, but most studies indicate that the joints formed independently (Parker, 1942, p. 388-391; Hodgson, 1961b, p. 26; DeSitter, 1964, p. 99-111).

There is growing realization that the fundamental fracture pattern of a rock mass is established early in its history. Some or all of the original fracture sets within a rock mass may be subsequently more or less tightly welded together by compressive stress within the Earth's crust. As a rock mass is gradually unloaded and exposed by erosion only a fraction of the total number of original joints will be reopened. Moreover selective structural or erosive processes may utilize and open up a few of the original sets while other sets remain closed. Therefore the joint fractures which are initially apparent from the outward form of a single outcrop are not necessarily representative of the entire joint pattern originally developed in the rock (Chapman, 1958; Wise, 1964, p. 295-296).

A fundamental problem.—Geologic evidence suggests that jointing is a fundamental and widespread process which inevitably affects rock masses as soon as they attain a brittle state regardless of the depth of burial. Moreover the general lack of lateral displacement as well as the plumose surface markings suggest that joints are natural tension fractures. This interpretation has not been universally accepted in the past because theoretical considerations have indicated that absolute tension is impossible below very shallow depths in the Earth's crust (Anderson, 1951, p. 159; Hubbert, 1951, p. 367). This apparent conflict between observation and theory is resolved when the role of fluid pressure in the tension fracturing process is considered.

A FAILURE ENVELOPE FOR ROCKS

One of the easiest ways to represent the stress conditions required for brittle fracture in rocks is by means of a failure envelope. Natural fracturing can occur in response to principal stresses which are either tensile or compressive. Therefore an envelope predicting failure under all stress conditions would be most useful. Such an envelope is provided by the Griffith theory of fracture (Griffith, 1921, 1925; Orowan, 1960, p. 329-333; Odé, 1960, p. 294-300; Brace, 1960).

The Griffith theory is based on the assumption that solids are filled with minute cracks. When differential stress of a certain magnitude exists, high tensile stress will occur near the ends of such cracks, even when all the principal stresses are compressive. Failure occurs by growth of cracks in response to this tension. The envelope predicted by the Griffith theory has the equation:

$$\tau^2 - 4K\sigma - 4K^2 = 0 \qquad (1)$$

where $-K$ is the tensile strength, and τ and σ are the shear and normal components of stress on the plane of the most critically oriented cracks, with tensile stress considered negative. This equation is plotted as a failure envelope in figure 1.

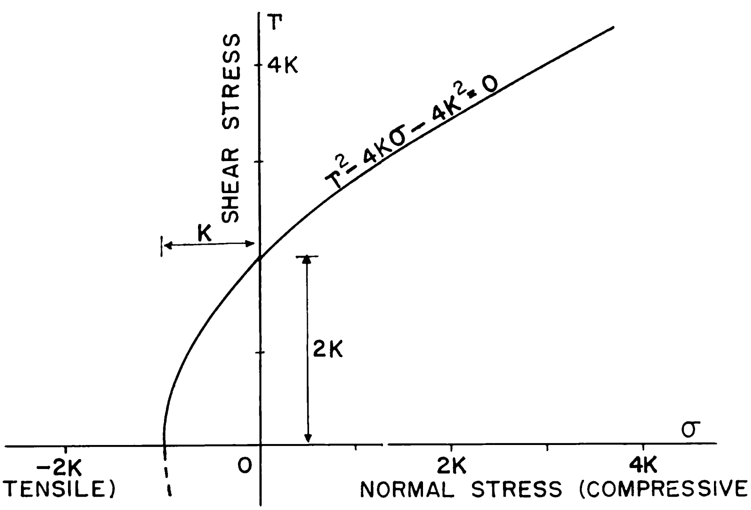

Fig. 1. The Griffith failure envelope. $-K$ is the tensile strength.

The results of many triaxial tests performed on rocks in recent years indicate that the Griffith theory predicts failure stresses that are too low in the compression region. The theory has been modified by McClintock and Walsh (1962) (see also Brace, 1960) in order to give a more realistic model of rock behavior in compression. McClintock and Walsh revised the Griffith theory to include the effect of frictional forces along the walls of cracks closed in compression and found that the resulting failure envelope would be a straight line.

A composite failure envelope, parabolic in the tension region and a straight line in the compression region, will therefore agree closely with both theory and experimental data. In constructing this composite envelope it is convenient to connect the parabolic segment to the straight line at a point where they both have the same slope. The position of the point of tangency therefore depends on the slope chosen for the straight line portion of the envelope. The average slope of experimentally determined failure envelopes is about 30° (Hubbert and Rubey, 1959, p. 124), and this value will be used for the remainder of this study. The point of tangency between the parabolic and straight line parts of the envelope will occur at $\sigma = +2K$, $\tau = \pm 2\sqrt{3}K$. This composite envelope is shown in figure 2. The equation for the straight line part of this envelope with a slope of 30° is:

$$\tau = \frac{4}{\sqrt{3}} K + \frac{1}{\sqrt{3}} \sigma \qquad (2)$$

It is well to remember that the composite failure envelope (fig. 2) is an approximation to an exceedingly complex natural phenomenon. In deriving and using this envelope we are forced to make a number of simplifying assumptions which may not be justified in all cases.

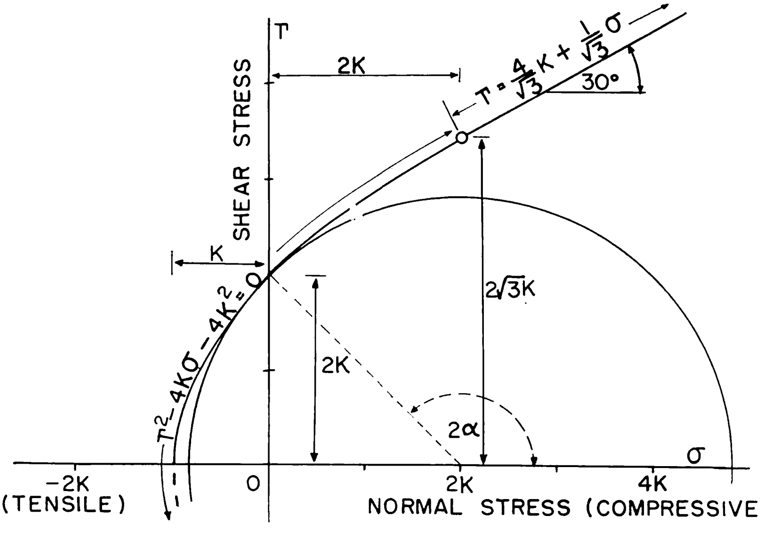

Fig. 2. The composite failure envelope.

The Griffith theory itself introduces the assumption that fracturing occurs by growth of cracks in rock due to stress concentrations at crack tips. This mechanism probably can be applied to the brittle fracturing of rocks in the upper part of the Earth's crust (Brace, 1964), but it may be unrealistic under conditions where deformation occurs by twinning and translation gliding of the component mineral grains in a rock.

Another basic assumption inherent in the failure envelope approach to fracturing is that the mechanical behavior of rock at the time of fracture is dependent only on the magnitude of the greatest and least principal stresses, whereas experimental tests indicate that temperature, the magnitude of the intermediate principal stress, and the pressure of internal pore fluids can also influence the mechanical behavior of rock (Handin and Hager, 1958; Handin and others, 1963; Handin, Heard, and Magourik, 1965). As will be shown in the next section, the effect of internal pore pressure can be incorporated into a failure envelope analysis if the envelope is regarded as a plot of the effective stresses required for rupture.

In the past failure envelopes have been used to predict the angular relationship between principal stress directions and fracture planes. For example, the angle 2α (fig. 2) between the compression axis and the radius to the point of tangency of a Mohr circle representing failure is presumably twice the angle from the direction of least principal stress to the failure plane. However triaxial tests indicate that in most cases the observed fracture planes deviate several degrees from the predicted orientation in both compression and extension tests (Griggs, Turner, and Heard, 1960, p. 53, 65; Heard, 1960, p. 226), so the assumption can be true only approximately. Brace (1960) has pointed out that the angle α predicts only the orientation of the most severely stressed Griffith cracks and does not predict how these cracks will grow and coalesce into a macroscopic fracture. Brace and Bombolakis (1963) have shown from photoelastic studies of uniaxial compression that a critically oriented Griffith crack will tend to grow out of the initial plane into an orientation parallel with the direction of compression where it ceases to propagate. Apparently the stresses necessary to initiate limited crack growth in compression are somewhat below the stresses required for the development of a through-going shear fracture.

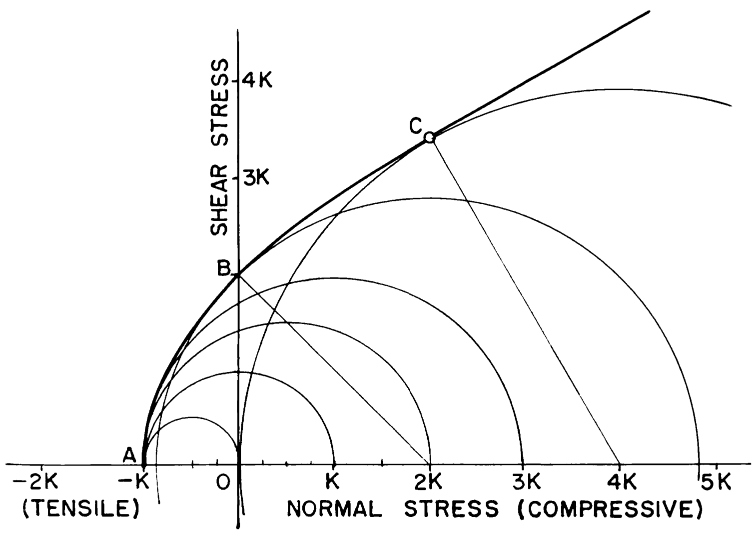

Fig. 3. The composite failure envelope showing a family of Mohr stress circles tangent at point A and one Mohr stress circle tangent at each of points B and C.

The experimental work of Brace (1964, p. 162-163) suggests that the angle α between the least principal stress direction and through-going shear fractures decreases gradually from about 90° to about 70° as the point of tangency of Mohr circles representing failure moves along the failure envelope from points A to B and C (fig. 3), although there is only approximate correlation with the exact value of α predicted from the failure envelope.

Clearly the failure envelope presented in figures 2 and 3 is only an approximation to an exceedingly complex natural phenomenon, useful in predicting the approximate stress conditions required for certain kinds of fracture, but restricted in its use both because it does not include the effects of other variable quantities that influence the fracturing process and because it predicts fracture orientation only approximately.

ROLE OF FLUID PRESSURE IN FRACTURING

Internal pore pressure is one of the most important variables affecting the strength of brittle solids. This fact has come to be appreciated by geologists only recently. Hubbert and Rubey (1959) developed the basic mechanics of pore pressure phenomena. The results of their work indicate that the total normal stress (S) across any plane in fluid saturated rock can be resolved into an effective normal stress (σ) and an internal pore pressure (p). These quantities are related by equation (3):

$$\sigma = S - p \tag{3}$$

The importance of equation (3) is that fracturing in brittle materials is apparently controlled by critical effective stresses and is only indirectly related to either the total stress or the fluid pressure. Jaeger (1962, p. 169-170) arrived at this same result through a derivation based on the Griffith theory with the additional assumption that the Griffith cracks are filled with a fluid of pressure (p). This theoretical prediction that fracturing is controlled by critical effective stresses has been experimentally confirmed by Handin and others (1963) and by Jaeger (1963). A failure envelope as in figures 1 to 3 must therefore prescribe limiting *effective* stresses for fracture when applied to the fracturing of rocks with internal pore pressure.

STRESS VARIATION IN THE EARTH'S CRUST

The range of possible stress variation in the Earth's crust at a particular depth is limited by two conditions. The first of these is that the stresses shall not exceed the rock strength (as approximately prescribed by the failure envelope in figs. 2 and 3). The second condition is that the stress system must conform to the Earth's surface, which is a surface of nearly zero normal stress and no shear. If it is assumed that the Earth's surface is a flat horizontal plane, one of the total principal stresses must be vertical and approximately equal to the bulk weight per unit area of the overburden to the depth considered. Thus:

$$S_{vert} = \rho_B\, g\, d \tag{4}$$

where S_{vert} is the total vertical principal stress, ρ_B is the bulk density of fluid saturated rock, g is the acceleration of gravity, and d is the depth. Admittedly this approximation may be in error in regions of high relief or in regions undergoing intense deformation, but it is a good approximation over most of the

Earth's surface through most of geologic time. When considering stress variation in the Earth it is convenient to define a quantity λ as the ratio of fluid pressure to overburden weight per unit area. At a particular depth (d):

$$\lambda = \frac{p}{S_{vert}} = \frac{p}{\rho_B \, g \, d} \qquad (5)$$

Substituting equations (4) and (5) in equation (3):

$$\sigma_{vert} = \rho_B \, g \, d \, (1 - \lambda) \qquad (6)$$

we obtain an expression for the vertical effective principal stress in terms of depth, density, and ratio of fluid pressure to overburden weight. Equation (6) specifies that one of the principal effective stresses be vertical and equal to $\rho_B \, g \, d(1 - \lambda)$. Figure 4 shows the three stress systems that satisfy this condition.

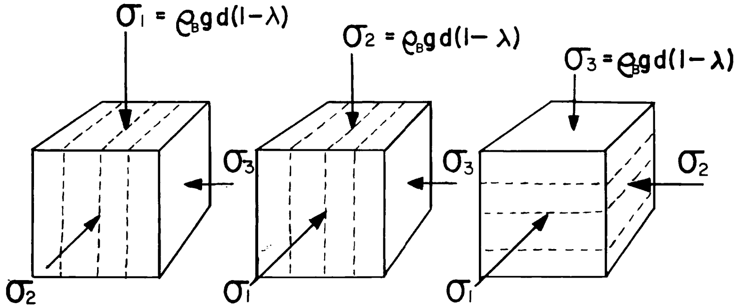

Fig. 4. Three possible effective principal stress configurations in the Earth's crust. σ_1 is the greatest effective principal stress, σ_2 is the intermediate effective principal stress, and σ_3 is the least effective principal stress.

NATURAL TENSION FRACTURING

Theory and experimental evidence.—Jaeger (1963) has performed a series of experiments on unjacketed rock cylinders in a pinching-off apparatus with an additional axial stress applied to the test specimen. He found that tension fractures formed perpendicular to the axis of the cylinders whenever the effective axial stress decreased somewhat below the tensile strength of the rock being tested. This result is in essential agreement with the Griffith theory of fracture. The failure criterion for tension fracturing may therefore be taken as:

$$\sigma_3 = -K \qquad (7)$$

where σ_3 is the least effective principal stress, and $-K$ is the tensile strength. Tension fracturing presumably can occur anywhere in the Earth's crust where this condition is satisfied.

On the composite failure envelope (fig. 3) tension fracturing will occur when a Mohr circle is tangent at point A. In figure 3 a family of such circles has been drawn. The geometric properties of the envelope are such that the largest stress circle that can be tangent at point A is centered at $+K$ and intersects the compression side of the abscissa at $+3K$. This value of $+3K$ is therefore the effective principal stress of greatest magnitude that can occur in rock undergoing tension fracturing. Tension fractures can therefore form in the Earth's crust only down to the depth where the magnitude of the greatest principal stress exceeds +3K. At the maximum depth for tension fracturing:

$$\sigma_1 = +3K \tag{8}$$

Maximum depth formulas.—Equations (6) and (8) place a limit on the maximum depth in the Earth's crust where tension fracturing can occur. If the stress conditions are such that σ_1 is vertical:

$$\sigma_1 = \rho_B\, g\, d\, (1 - \lambda) \tag{9}$$

Substituting equation (8):

$$+3K = \rho_B\, g\, d\, (1 - \lambda) \tag{10}$$

or:

$$d_{max} = \frac{+3K}{\rho_B\, g\, (1 - \lambda)} \tag{11}$$

we obtain an expression for the maximum depth to which tension fracturing can occur for the case σ_1 vertical. If σ_2 is vertical and if σ_1 is n times greater than σ_2:

$$\sigma_2 = \rho_B\, g\, d\, (1 - \lambda) \tag{12}$$

$$\sigma_1 = n\rho_B\, g\, d\, (1 - \lambda) \tag{13}$$

Substituting equation (8):

$$d_{max} = \frac{3K}{n\rho_B\, g\, (1 - \lambda)} \tag{14}$$

we obtain an expression for the maximum depth to which tension fracturing can occur for the case σ_2 vertical. In the case σ_3 vertical, tension fractures probably would not form because λ values exceeding one would be required for the development of tensile stress. Equation (11) is plotted in figure 5 for several arbitrary values of K. In figure 6 equation (14) is plotted for values of n of 1, 2, 4, and 8 assuming a bulk rock specific weight of 144 lbs/cu ft and a tensile strength of -2.88×10^5 lbs/sq ft.

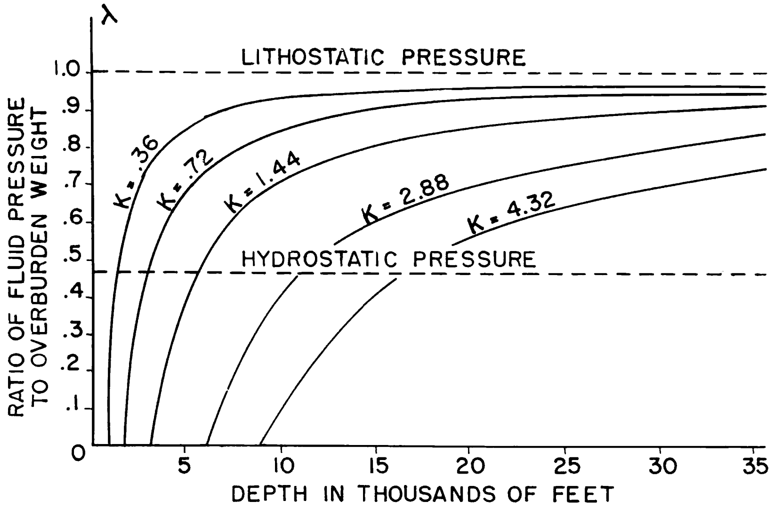

Fig. 5. A graph for the case σ_1 vertical, showing the maximum depth in the Earth where tension fracturing can occur for various tensile strengths. The specific rock weight is 144 lbs/cu ft. –K is the tensile strength in 10^5 lbs/sq ft.

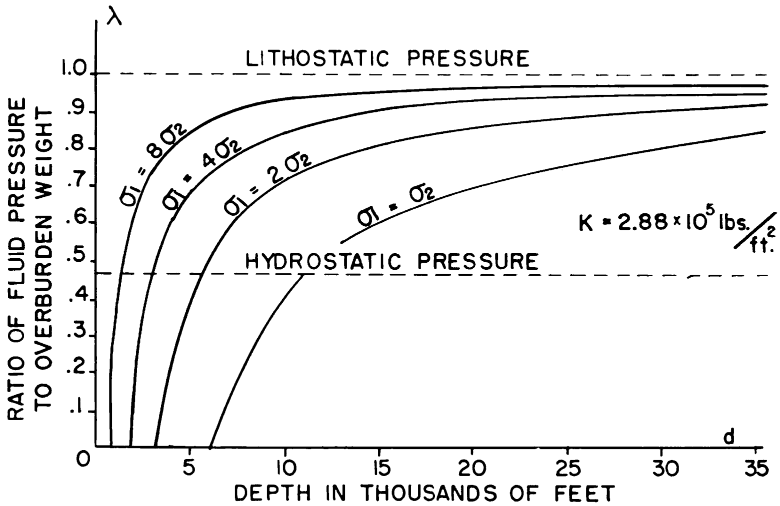

Fig. 6. A graph for the case σ_2 vertical, showing the maximum depth in the Earth where tension fracturing can occur for various assumed ratios of σ_1 to σ_2. The assumed tensile strength is -2.88×10^5 lbs/sq ft, and the specific bulk rock weight is 144 lbs/cu ft.

The plots in figures 5 and 6 indicate that a hydrostatic fluid pressure distribution will permit the development of tension fractures to a depth of several thousand feet. As the ratio of fluid pressure to overburden weight approaches one, the maximum depth to which tension fracturing can occur becomes very great, even for exceedingly weak rocks. However, for a specific value of λ less than one, the maximum depth for tension fracturing becomes increasingly shallower as the quantity n becomes larger.

In the past geologists have been reluctant to assign a tensile origin to joints because of the supposed impossibility of a pervasive tensile stress at depth in the Earth's crust. However the preceding analysis has shown that effective tension fracturing is possible at depth and requires fluid pressure-overburden weight ratios no greater than those observed in deep oil wells. It is concluded that the depth requirement is no longer an obstacle to interpreting joints as tension fractures.

Open fractures.—When a Mohr stress circle is tangent at point C (fig. 3) the greatest and least effective principal stresses are 8K and zero respectively. Equations (15) and (16) therefore give the maximum depth in the Earth where effective tension

$$d_{max} = \frac{8K}{\rho_B\, g\, (1-\lambda)} \quad (15) \qquad d_{max} = \frac{8K}{n\rho_B\, g\, (1-\lambda)} \quad (16)$$

can occur for the cases σ_1 vertical and σ_2 vertical respectively. Equation (15) is plotted in figure 7 for a specific bulk weight of 144 lbs/cu ft and for several arbitrarily chosen values of K. Again the graph indicates that open fractures can occur to great depth, even with only moderately high fluid pressure-overburden weight ratios. Such open fractures could play a fundamental role in veining and in the migration of hydrothermal fluids, petroleum, and ground water.

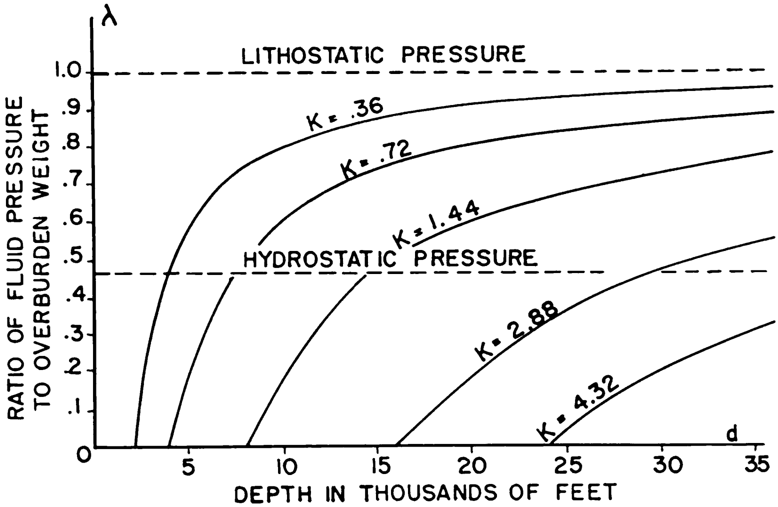

Fig. 7. A graph for the case σ_1 vertical showing the maximum depth in the Earth where open fractures can occur, for a variety of tensile strengths. The specific bulk rock weight is 144 lbs/cu ft.– K is the tensile strength in 10^5 lbs/sq ft.

SYNTHESIS

During a cycle of sedimentary accumulation and in the subsequent deformation a number of processes are operative which tend to increase the ratio of fluid pressure to overburden weight (Rubey and Hubbert, 1959, p. 173-185; Heard and Rubey, 1963; Zen and Hanshaw, 1964; Rubey and Hubbert, 1965). Figure 8 shows the effect of an incremental increase in fluid pressure

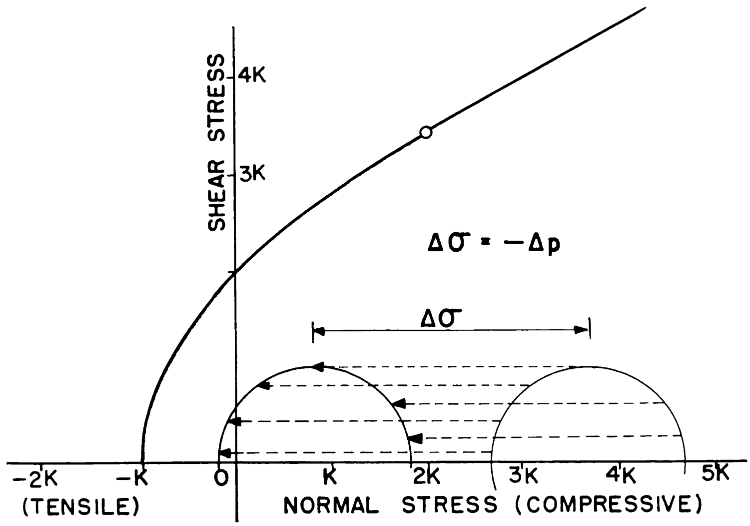

Fig. 8. A failure envelope diagram showing the effect of an incremental increase of fluid pressure on the position of the Mohr stress circle, assuming that the total principal stresses remain constant.

on the position of a Mohr stress circle with respect to the failure envelope, assuming constant total principal stresses (see also Hubbert and Rubey, 1960, p. 627). In an environment where the ratio of fluid pressure to overburden weight is constantly increasing, a Mohr stress circle will be repeatedly driven against the failure envelope. If the stress circle is large it will be tangent to the right of the ordinate (fig. 8) and shear fracturing will occur. Depending on the relative positions of σ_1, σ_2, and σ_3 either normal, thrust, or strike-slip faulting could occur (Hubbert, 1951; Anderson, 1951; Hubbert and Rubey, 1959). Conversely, if the diameter of the stress circle is small it will be tangent to the failure parabola at the point where it crosses the abscissa, and natural tension fractures or joints will form. This may explain the abundance of joints in the near-horizontal strata of cratonic regions where the differential stress has never been large enough to induce widespread faulting. The tendency toward increase in fluid pressure present in most rocks during the sedimentary cycle may account for the universality of jointing as compared with other kinds of structural deformation. If a horizontal least principal stress direction changes while the ratio of fluid pressure to overburden weight is increasing a number of sets of vertical tension fractures may form. The analysis presented in earlier sections of this paper indicates that natural tension fractures as postulated here are possible at great depth in the Earth providing the ratio of fluid pressure to overburden weight approaches one. Theory also indicates that previously formed fractures may be opened up by high fluid pressure at depth in the Earth's crust, and these open fractures may act as plane conduits for the migration of ground water, ore fluids, and hydrocarbons.

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