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Objekttyp: **Article**

Zeitschrift: **Bulletin der Vereinigung Schweiz. Petroleum-Geologen und -Ingenieure**

Band (Jahr): **49 (1983)**

Heft 116

PDF erstellt am: **21.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-207415

Bull. Ver. schweiz. Petroleum-Geol. u. -Ing., Vol. 49, Nr. 116, April 1983, S. 29 – 35

Remarks by a Geologist on the Propagation and Containment of Extension Fractures

with 5 figs.

by P. E. GRETENER*

Zusammenfassung

Bei der Untersuchung von Klüften ist es vorteilhaft, zwischen Zerrklüften und Injektionsklüften zu unterscheiden. Die ersteren werden durch jede vorhandene Diskontinuität (Bruch, Kluft, Schichtfläche) beschränkt, die letzteren nur durch solche Diskontinuitäten, die gleichzeitig Spannungsfelder abgrenzen.

Abstract

When considering extension fractures (joints) it is important to distinguish between matrix-stress fractures and hydraulic fractures. The former will be contained by any pre-existing discontinuity (fault, joint, bedding plane), the latter only by those discontinuities that separate different stress regimes.

1. Introduction

Recently a flurry of papers (PRATS, 1981; TEUFEL and CLARK, 1981; WARPINSKI et al., 1982; KRY and GRONSETH, 1983) has appeared on the above subject. While the experimental results of these new engineering investigations are welcome, it nonetheless seems appropriate to point out that much of the basic process has been known to geologists for some time. In fact, while not explicitly stated, much flows from the delightful analysis written by E. M. ANDERSON (1951) some thirty years ago. Thus the following brief note, intended to add clarification to this controversial subject, seems in order.

When examining extension fractures it is necessary to make the distinction between matrix-stress fractures and hydraulic fractures. Both types occur as natural and also as man-made phenomena. The term „matrix-stress fracture" may require some definition. It refers to those extension fractures initiated and propagated in a rock where external forces produce a tensile matrix stress. In general this tensile stress will be extremely low since it is well known that rocks are notoriously weak in tension. The hydraulic fractures in contrast are initiated by a local excess fluid pressure and they are propagated by the same excess fluid pressure within the growing crack. Even though there exists a high tensile stress at the tip of both types of fractures, the process of initiation and propagation is fundamentally different and leads to important discrepancies in behaviour.

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2. Matrix-Stress Fractures

Matrix-stress fractures are produced whenever a rock is placed into tension. A prime example are the beams within a sedimentary sequence which undergo bending or buckling. In either case tensile stresses will develop on the external side of individual bends. Once an extension fracture (joint) has been formed it will propagate and carry its own stress concentration as shown in Figure 1. Because of this local alteration of the virgin stress condition at the tip of the fracture such a crack can in fact cross the neutral fiber and propagate into the realm of compression on the inner side of a bend. In severe cases total separation of the beam may be the result. When such fractures encounter any pre-existing discontinuities their growth will be halted as shown in Figure 2. This has been known for decades and is systematically exploited by the civil engineers in the technique referred to as „pre-splitting". The application of this method calls for the creation of an artificial crack in the desired position before the full excavation of an underground opening or a road cut is carried out. The technique requires that a line of closely spaced, parallel boreholes is prepared. These holes are subsequently loaded from bottom to top with a low density explosive. The extended charges are set off simultaneously using electric detonators. The resulting plane shock wave front produces the desired pre-split that will limit the final excavation. The procedure is employed world-wide and can be witnessed in every modern road cut where the inner halves of the boreholes are nicely preserved as a series of man-made „worm tubes" (Figure 3).

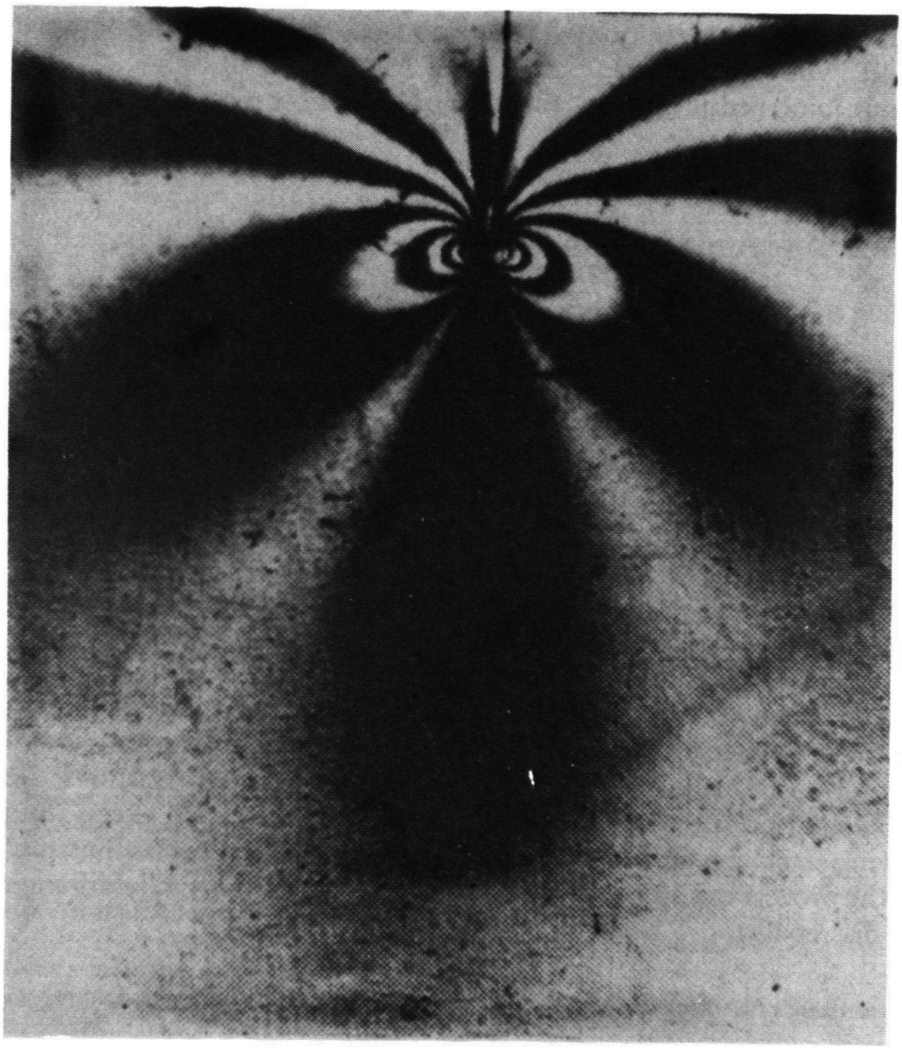


Fig. 1
Stress concentration at the tip of an open fracture as seen in a photo-elastic model.

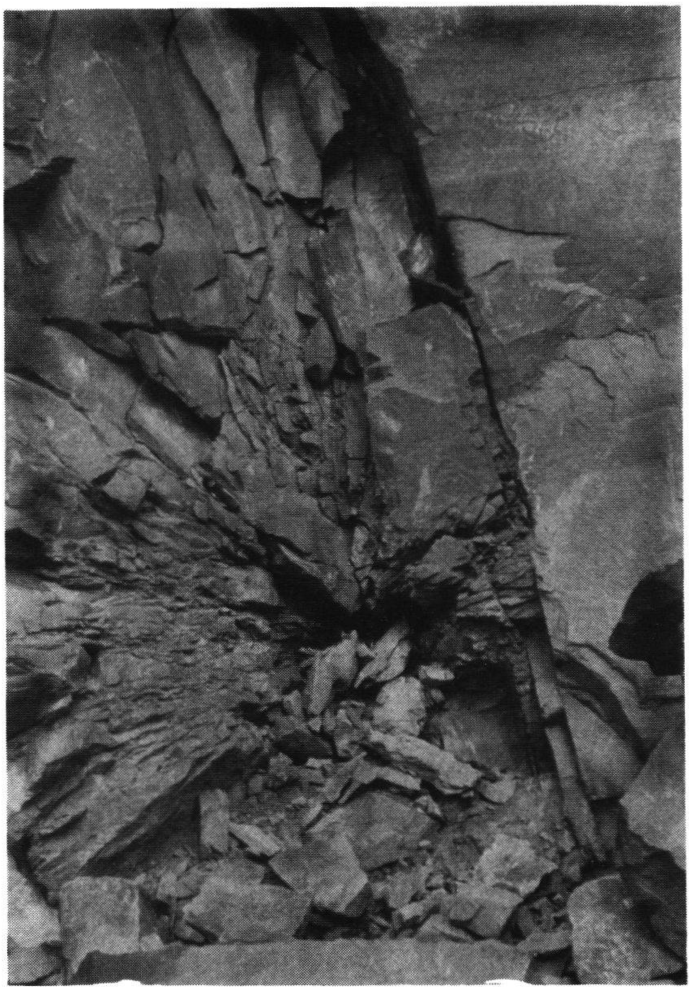
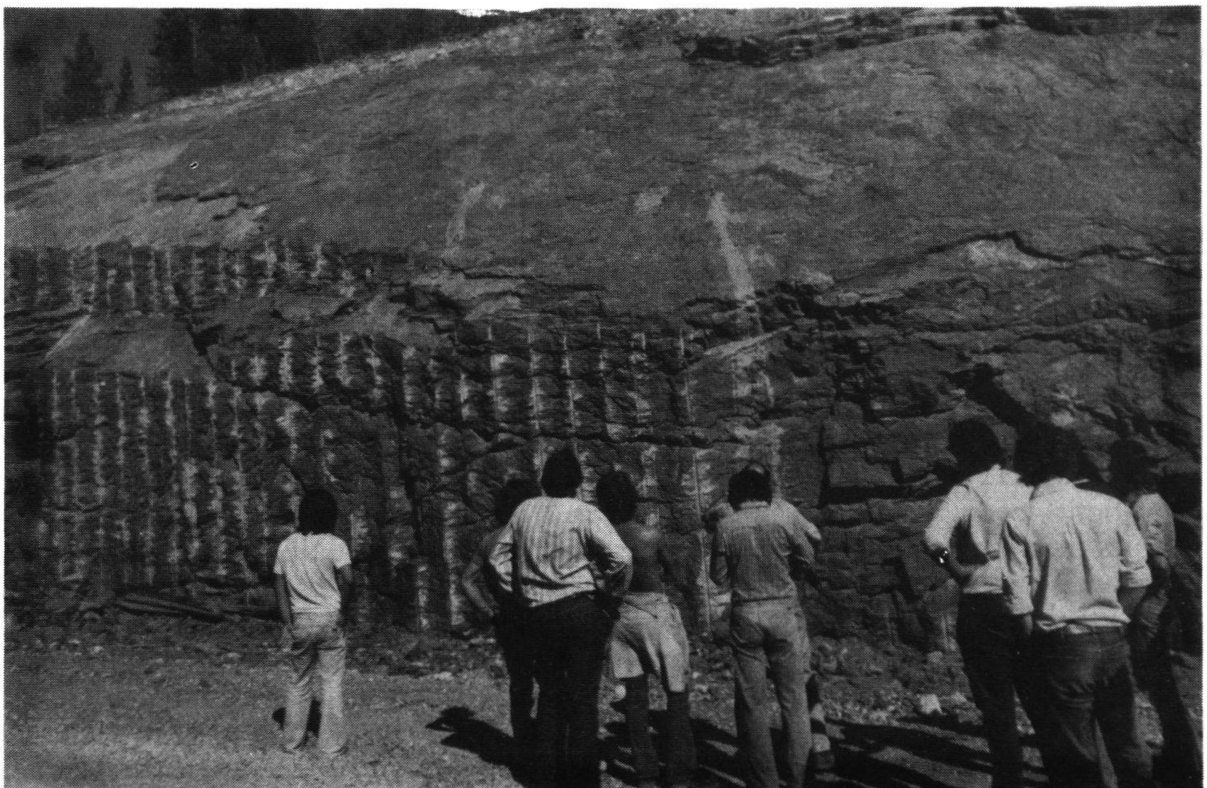


Fig. 2

Blast hole in a quarry wall. Note how the fractures radiating from the hole have been arrested by the pre-existing crack on the right hand side of the photo. A natural pre-split. For size: pocket knife left of centre.

Fig. 3

A road cut with man-made „worm tubes". A pre-split was used to obtain a smooth face in the desired location. This technique is used world-wide.



The stress concentration at the tip of such a propagating fracture (Figure 1) is caused by the small radius of curvature of the opening in that particular position. In earlier days (when were still poor) cracks in large plate glass windows were stabilized by drilling a hole into the tip of the fracture thus enlarging the radius of curvature and preventing further growth of the crack.

In summary it can be said that this process is well understood. It is recognized that such fractures will be stopped by any pre-existing discontinuity, simply because the stress concentration at the tip of the growing fracture is destroyed as it emerges into the existing crack. Since this particular fracture mechanism does not permit any regeneration of the stress concentration the fracture will be arrested.

3. Hydraulic Fractures

The case of hydraulic fractures is quite different. In nature this process refers to the formation of dikes and stills, in the case of man-made fractures one primarily thinks of the oil well stimulating process referred to as hydrofracturing. In each case the fluid pressure in the fracture is in excess of that prevailing in the surrounding rock. A uniform high fluid pressure does not lead to hydraulic fracturing of the rock or to dike formation despite a misconception to that effect by some authors.

I have long ago surmised that hydraulic fractures will not terminate at ordinary discontinuities (GRETENER, 1977). To my embarrassment I later discovered that this had been clearly demonstrated by the experiments of LAMONT and JESSEN as early as 1963. My own conclusions were based on theoretical considerations (Figure 4) and observations that dikes will frequently ignore bedding planes in their path (MUDGE 1968, p. 316/317). In hydraulic fractures the stress concentration at the tip of the fracture is maintained and if necessary regenerated by the excess fluid pressure within the crack. Intersection of an existing fracture will lead to a momentary small build-up of pressure in the hydraulic fracture. This will result in a slight widening of that fracture and will permit limited penetration into the existing fracture. At a suitably oriented protrusion (irregularity) of the latter the stress concentration at the tip will be renewed and the fracture will continue to propagate in the minimum energy orientation, i.e. perpendicular to the least compressive stress (σ_3) as predicted by ANDERSON (1951). At a discontinuity one may, therefore, expect a small deflection or sidestepping, such as shown schematically in Figure 4, but not a termination. What then, if anything, contains such a fracture?

The answer to this question is simple: „A bedding plane separating different lithologies". The latter term infers that the discontinuity separates materials with different mechanical properties. Under uniform boundary conditions of stress (compression, extension, or simple gravitational loading) such beds are apt to be in a different state of stress. Thus hydraulic fractures are contained by stress barriers as suggested by GRETENER (1969, 1977). If the minimum principal horizontal stress in the adjoining beds is larger than in the bed occupied by the vertical fracture, the latter will remained confined to the bed where it has originated. The case of basalt dikes differs only insofar as the excess magma pressure is quite large and the dike will move through the bedding planes and simply reflect the varying minimum horizontal stress by its changing width. Only where such a dike encounters an absolute stress barrier, where both effective horizontal stresses exced the effective overburden stress, will it turn into a sill (GRETENER 1969).

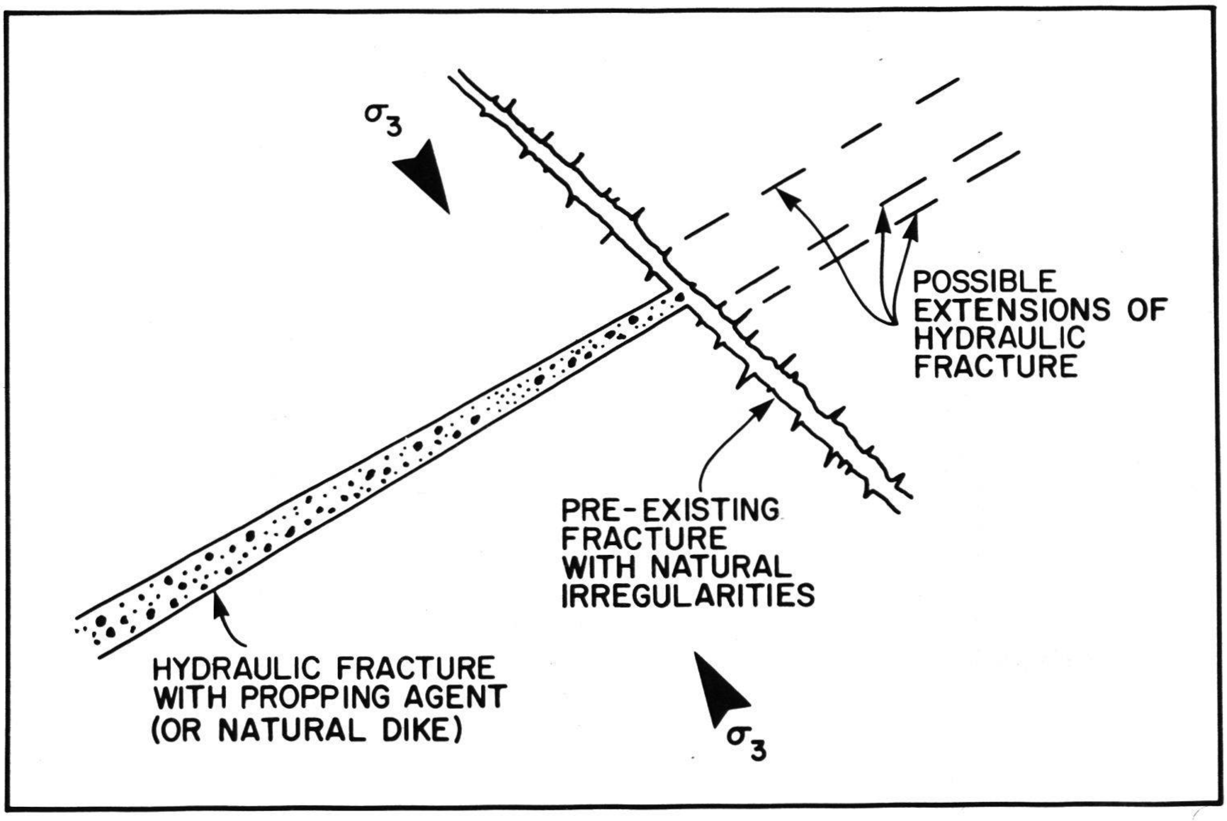


Fig. 4 A hydraulic fracture encountering a pre-existing crack. The roughness of the latter wil assure continuation of the hydraulic fracture. A minor offset may occur. This behaviour of hydraulic fractures is demonstrated by the experiments of LAMONT and JESSEN (1963) and is suggested by the observation that natural dikes tend to ignore both bedding planes and existing fractures. σ_3 gives the direction of the minimum compressive stress.

4. Consequences for Well Fracturing

For decades low permeability oil and/or gas reservoirs have been stimulated by hydraulic fracturing. It also has been quite clear from the early days on that most of the fractures induced by this process have a vertical orientation (HUBBERT and WILLIS, 1957). Obviously this process could hardly be successful if such fractures commonly were to split the seal, thereby depleting the reservoir. Yet the wide spread application of this technique attests to its effectiveness. The conclusion is, therefore, inevitable that these fractures by and large must be confined to the reservoir. Since caprocks such as shales are usually more ductile than the reservoir rocks one may expect the minimum principal horizontal stress to be higher thus confining the fractures to the reservoir. The confusion arises from the fact that there is still a widely held misconception that not only the effective overburden stress but also the effective horizontal stresses are a continuous function of depth. That this view is still held by some can be seen in such recent papers as: MAGARA (1981), and BRECKELS and VAN EEKELEN (1982). This is certainly an unreasonable expectation as shown by GRETENER (1969) and Figure 5 demonstrates once more what reality must look like in principal.

Before leaving this topic one might also point out that Figure 1 contains a message for all those that attempt to stimulate oil/gas wells by explosive fracturing. In view of the fact that almost all rocks are cut by fracture sets to a varying degree, one is tempted to forecast little success for this torture treatment by brute force.

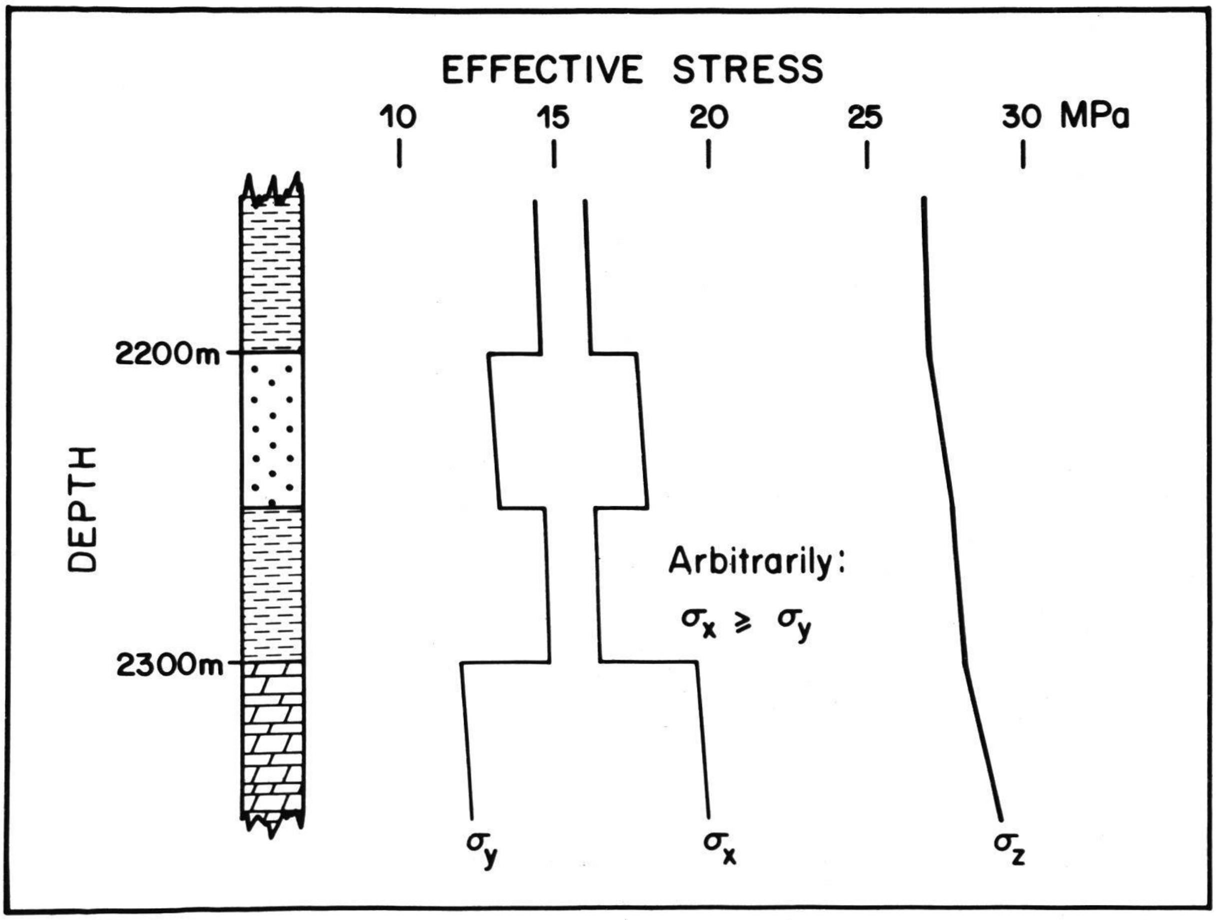


Fig. 5 A schematic view of the effective principal stresses in a layered sedimentary sequence. The effective overburden stress (σ_z) is a continuous function of depth. This is NOT the case for the principal lateral effective stresses (σ_x and σ_y) which must change abruptly at bedding planes separating different lithologies. This is true for all tectonic realms, be it compression, extension, or simple gravitational loading.

5. The Elusive Fracturing Gradient

This irregular and unpredictable distribution of the principal lateral stresses also has ramifications for the determination of the so-called fracturing gradient, an elusive quantity at best. It is of course these lateral stresses that determine the excess pressure required in an open hole to initiate a vertical fracture (HUBBERT and WILLIS, 1957). Such fracturing may be caused deliberately in order to stimulate production or else inadvertently when drilling into geopressures resulting in a lost circulation problem. The discontinuous nature of the principal lateral stresses makes it clear that any attempt at the precise prediction of the fracturing gradient must be a futile exercise. ANDERSON et al. (1973, p. 1267) grudgingly admit to this fact when they conclude: „Field measurements show that fracture pressure varies over a substantial range at a given depth in the same geological field. This variation is not accounted for by present methods of predicting the fracture pressure gradient, which do not take into account the varying mechanical properties of the formations". Of course it is not so much the changing mechanical properties *per se* as the resulting stress differences that control the breakdown pressure for the various lithological units. It is obvious that the fracture gradient *cannot possibly* be a smooth function of depth and all attempts to force such a function upon the measured data (where available) are doomed to failure. The observed large fluctuations (FERTL, 1976, p. 247 and 254) are in fact anticipated by theoretical considerations.

6. Conclusions

1. Matrix-stress fractures may spread outside the realm of the tensile stress regime due to the high stress concentration prevalent at the tip of such fractures. Inevitably, however, such fractures will terminate at any pre-existing discontinuity since the stress concentration at the tip of the fracture is irretrievably lost.

2. Hydraulic fractures can propagate across discontinuities since the stress concentration at the tip of the fracture can be regenerated by the internal excess fluid pressure. Such fractures are contained by stress barriers, i. e. those discontinuities that separate different stress domains.

3. The horizontal principal stresses are not a continuous function of depth regardless of the tectonic setting, be it compressive, extensional, or simple gravitational loading. This precludes any precise forecast of the fracturing gradient as a function of depth.

4. The recent papers by PRATS (1981), TEUFEL and CLARK (1981), WARPINSKI et al. (1982), and KRY and GRONSETH (1983) present welcome confirmation and additional evidence for a theme which has been known for quite some time. These papers demonstrate that a closer cooperation between geologists and engineers is badly needed.

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Acknowledgment

My good friend Felix FREY, fellow member of the Calgary Chapter of the Swiss Mafia, has again done his best to keep me honest, not an easy job with those academic egotists. I thank him for his help and his continued patience.