Macrofractures and fluid flow

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Macrofractures and fluid flow

with 6 figures

by P.E. GRETENER[1]

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Abstract

Evidence is presented that fractures, in particular joints, play a much more significant role in subsurface fluid flow than is generally accepted. Fractures produce little porosity but increase permeability dramatically. Both field observations and theoretical considerations force upon us the conclusion that open fractures are a key element in facilitating subsurface fluid movements.

Zusammenfassung

Es wird gezeigt, dass Brüche, insbesondere Zerrklüfte, für die Bewegung der Porenflüssigkeit von grosser Wichtigkeit sind. Solche Klüfte produzieren nur wenig zusätzliche Porosität, verbessern aber die Gesteinspermeabilität ganz erheblich. Sowohl Feldbeobachtungen, wie theoretische Überlegungen zwingen uns zur Schlussfolgerung, dass offene Zerrklüfte eine entscheidende Rolle spielen in der Dynamik der Porenflüssigkeit im Untergrund.

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1. Introduction

In engineering geology it has long been customary to make the distinction between *Rock and Rock Mass*. Unfortunately the term «rock» has a dual meaning; it designates a material but also size: the hand specimen, the laboratory sample, the tool or weapon of early man. The term «rock mass» quite clearly refers to a large volume of material consisting of rock. The «rock» can be tested in the laboratory, the «rock mass» can only be evaluated by in situ tests (GRETENER, 1981). In particular, the «rock mass» ranging in volume from a few cubic metres to cubic kilometres contains discontinuities, such as bedding planes, faults, joints, and cleavage planes. It is these discontinuities that affect the «rock mass» profoundly and are the decisive factor for its physical behaviour. Thus, in slope stability it can be shown that most of the classic landslides of the world were induced on slopes with subparallel bedding planes or other discontinuities such as joints or cleavage systems (HEIM, 1919: Goldau slide, Switzerland; CRUDEN & KRAHN, 1973: Frank slide, Alberta, Canada; ALDEN, 1976: Gros Ventre slide, Wyoming, U.S.A; KIERSCH, 1976: Vajont slide, Italy). In the resource industry both the reservoir and the mining engineer deal with «rock masses» that cannot be properly investigated by studyng the «rock» in ever greater detail.

Of particular interest are the joint systems, fractures with no visible offset. Field observations demonstrate that virtually no rock is free of such systems. In fact, SCHEIDEGGER (1979) states the case very well in his introductory remarks where he notes: «Joints are ubiquitous phenomena. They are visible in every outcrop, road cut, mountain side in materials ranging from firm, solid plutonic rocks to extremely friable recent sediments.» The number of systems and the joint spacing is subject to large variations. Rock character (brittleness) has a pronounced effect (STEARNS, 1969) as well as bed thickness (HARRIS et al., 1960; LADEIRA and PRICE, 1981) and also tectonic history. However, it can be shown that at the levels of active human exploitation (<8 km) most rocks behave in a brittle fashion. It is also proven that rocks with a very tranquil tectonic history are nonetheless jointed. Thus the Paleozoic and Mesozoic rocks of the Grand Canyon area are strongly jointed and yet they have experienced little deformation beyond uplift. The Pleistocene rocks of the Bahamas platform are only weakly cemented and have seen no tectonic activity and yet they are strongly jointed (NEWELL & RIGBY, 1957; SCHEIDEGGER, 1977). The conclusion is inevitable that joint systems are an integral part of most rock masses regardless of their age and tectonic history. It is also obvious that joints may form during lithification (mudcracks, columnar jointing) or any time throughout the history of a rock mass. Strong tectonic deformation will result in severely jointed rocks, creating new systems and/or enhancing pre-existing ones.

Joints will affect all physical properties of a rocks mass profoundly. Such properties are: strength, sonic velocity, electrical resistivity, permeability, porosity, density, and others. The quantitative effect will depend on the fracture spacing (f_s) — or its inverse, the fracture frequency (f_f) — and the fracture width (f_w). Fractures may be open, closed, or healed. It is immediately evident that besides the parameters listed above the fracture condition will also have to be taken into consideration (f_o:open; f_c:closed; f_h:healed). Open fractures will affect all the above mentioned physical properties in a most dramatic manner. Closed fractures will still have some, but highly variable, effect. Healed fractures, depending on the nature of the cement, may have no effect, the effect similar to that of an open fracture, or in fact have an effect reverse to that of an open fracture. This topic will be discussed further on.

For this paper the effect of open fractures on the fluid flow, i.e. on permeability and porosity, is of primary interest. For the oil patch the vertical joints, present to a varying degree in all sediments, are of particular concern. These fractures are difficult to detect since most often they are oriented parallel or subparallel to the well bore. Direct intersection can only be expected when the fracture frequency is extremely high ($>5\ m^{-1}$) and most logging tools respond poorly, if at all, to such fractures, regardless of whether they have been intersected or pass close to the well.

The no-offset observation labels these fractures as tension cracks. In many cases this is difficult to understand when one finds that the sets, as viewed on the bedding plane, form the diamond pattern typical of shear fractures. Also, it is not at all clear what kind of forces must be called upon in order to produce these regional fracture systems in rocks that have not undergone any tectonic deformation. DRUMMOND (1964) p. 227, refers to these joints as «cryptic fractures as opposed to the (obvious) «tectonic fractures». SCHEIDEGGER's (1979) paper discusses these problems under the appropriate title: «The Enigma of Jointing». In my opinion even the «ancient» view of failure by fatigue under the influence of tidal forces cannot be ruled out particularly when one is prepared to accept VELIKOVSKY's (1950) «near miss theory» as improbable but not impossible. If this sounds a bit off key, let us not forget that even the respectable and well-known geophysicist Sir Edward BULLARD (1966) said: «With a system as complicated as the earth almost anything can happen occasionally.»

In addition, the following observation deserves to be recorded. Field studies of the Paleozoic carbonate rocks in the Front Ranges of the Canadian Rockies reveal what I have termed «fracture clusters». The phenomenon is shown schematically in Figure 1. For reasons unknown, patches of very intense fracturing alternate with areas of large fracture spacing. The scale on Figure 1 indicates that this matter may not be without significance in hydrocarbon exploitation when one considers the small cross sectional area of an oil well. Selective dolomitisation, dolomite being far more brittle than limestone (STEARNS, 1969, p. 86, Fig. 6), could be the answer, but this remains merely a speculation at this time.

It should also be pointed out that the case of *micro fracturing* as reported by KOZLOVSKY (1984) for the «Kola Well» and by WATTS (1983) for the chalks of the North Sea cannot be compared to the effect of macro joints. Micro fracturing produces a type of matrix porosity and permeability; it does not result in the continuous fluid conduits typical of a rock cut by macro joints. Since micro fracturing will be overprinted on the natural matrix porosity of a rock it too may result in a two-system porosity, but of quite a different character than the one created by the macro fractures.

In view of the fact that some conventional oil and most of the heavy oil and tar are produced from *weakly consolidated* reservoirs it should be re-emphasized that field observations demonstrate the presence of joints in such rocks. Shear fractures, not tension joints, may in fact be formed in loose sand, provided the latter is subject to confining pressure. This is clearly proven by the well-known experiment producing normal and reserve faults in «Hubbert sandbox» (HUBBERT, 1951). SCHOLZ (1968) has shown that dilatancy along the future fracture path precedes the actual formation of these shear fractures (faults). Thus one must conclude that even in loose, completely unconsolidated, but confined materials (any subsurface reservoir is confined) fractures of the shear type may form and provide fluid conduits.

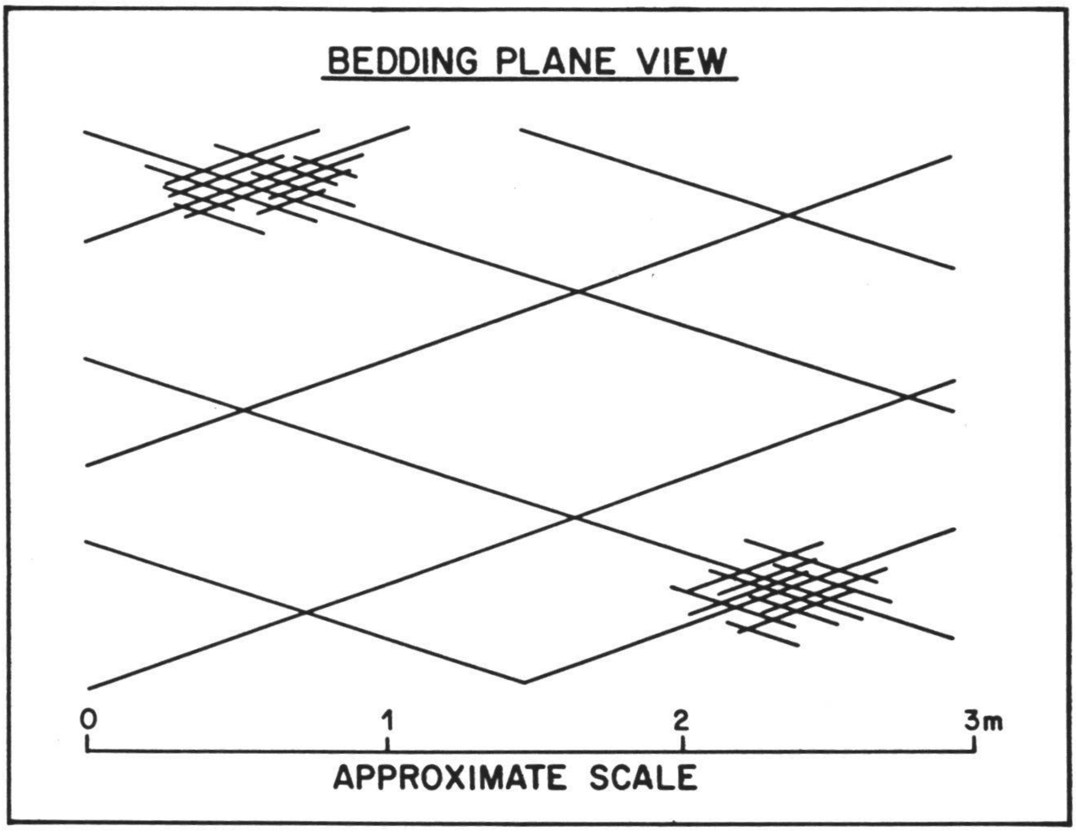

FIGURE 1 A schematic representation of the «fracture clusters» as observed in many Paleozoic carbonate rocks in the Front Ranges of the Southern Canadian Rocky Mountains. Their origin remains obscure.

2. Fractured hydrocarbon reservoirs

Such reservoirs are presently recognized but they are considered to be a special case containing only a small fraction of the world's total hydrocarbon reserves. DRUMMOND (1964) states: «More than ten percent of world reserves occur in fractured fields in the Middle East. The world total is probably still greater, but is difficult to evaluate.» This view has not changed markedly over the years. In older and more recent publications on the subject (HUBBERT & WILLIS, 1955; AGUILERA, 1980; VAN GOLF-RACHT, 1982) the same names keep reoccurring: Spraberry field, Texas; Monterey Formation, California; Asmari and related carbonates of the Middle East; and more recently, Reforma limestone of Mexico. Surprisingly, the ultimate fractured reservoir, the Gilsonite dikes of Colorado-Utah (DAVIS, 1957), has received little attention. In this case the oil (now Gilsonite) occours in widely spaced, parallel fractures up to 5 m wide.

I may have overstated the case when I previously said: «There is no such thing as an unfractured reservoir.» However, the observations noted in the introduction lead us to suspect that fractures play a far greater role than what they are presently given credit for. The disregard for fractures as shown in the book on production operations by ALLEN and ROBERTS (1978) is certainly unacceptable.

A resurgence of interest in the literature seems to support this view. Two quotes from recent papers will suffice to make the point. In their summary, KEMPTHORNE and IRISH (1981) state the following regarding the Norman Wells oil field (NWT, Canada): «Information from oriented cores, well tests, fluid and pressure surveys, outcrop studies, and surface photos have shown that natural vertical fractures present in the reservoir have a strong N30°E orientation. The proposed development plan will make use of the directional permeabilities resulting from natural fractures.» In the AAPG Explorer of November 1985 (ANON, 1985) a discussion of a well to be drilled in the Utah-Wyoming thrust belt is presented. The target is the very brittle Nugget sandstone. Mike Short of Amoco is quoted as having this to say: «the reservoir characteristics aren't the best, but on a structure like this we can expect fracture enhancement that will provide adequate porosity.»

In connection with recognized fractured reservoirs the term «lost circulation» is often metioned (REGAN, 1953, p. 203; DRUMMOND, 1964, p. 235). This is to be expected on theoretical grounds. If a well intersects the plumbing system in a reservoir containing open fractures, there is no stress protection for the overbalance of the mud. It is simply a case of balancing fluid pressures, quite analogous to the condition in a hard geopressure environment (DICKINSON, 1953; GRETENER & FENG, 1985). Since lost circulation is a frequent but not universal problem, one may argue against the widespread occurrence of fractured reservoirs. However, not in all instances will the well establish a connection to this natural plumbing system. In structurally complex areas fracture frequency may be highly variable over short distances. Under those conditions the well, representing only a point sample of the formation (a case of digital sampling!), may completely miss the fracture system. In areas lacking or of subdued tectonic deformation, fractures may be widely spaced and parallel to the well axis, thus also escaping direct intersection and leading to an isolation of the well from the fracture system. Even where open fractures are intersected they may be quickly sealed off by a mud cake, thus only allowing for very limited mud loss. It is easy to imagine why well reaction may not reveal the presence of a fractured reservoir. In conclusion: «lost circulation is a viable but not infallible indicator of the presence of a fractured reservoir.»

3. Effect of open fractures on permeability and porosity

In recent years three texts on fractured hydrocarbon reservoirs have been published (AGUILERA, 1980; REISS, 1980; VAN GOLF-RACHT, 1982). All of these books start with the simple model shown in Figure 2, a rock mass containing 3 orthogonal sets of open fractures. The nature of the fracturing of the rock mass is described by the fracture width (f_W) and the fracture spacing (f_S). The fractures themselves are treated as flat cracks. Table 1 gives the results for a specific case. The cube in Figure 2 has the dimension of one cubic metre, the fracture spacing is thus 1 m and the fracture width is taken as 10^{-3} m (1 mm). The result of the, granted extremely simplified, scenario as shown in Table 1 present a very forceful message: *effect on permeability (k) is profund, effect on porosity (n) is negligible.*

Table 1

f_S	f_W	$\Delta k_{x,y,z}$	Δn
1 m	10^{-3} m (1 mm)	160 D	0.003 (0.3%)

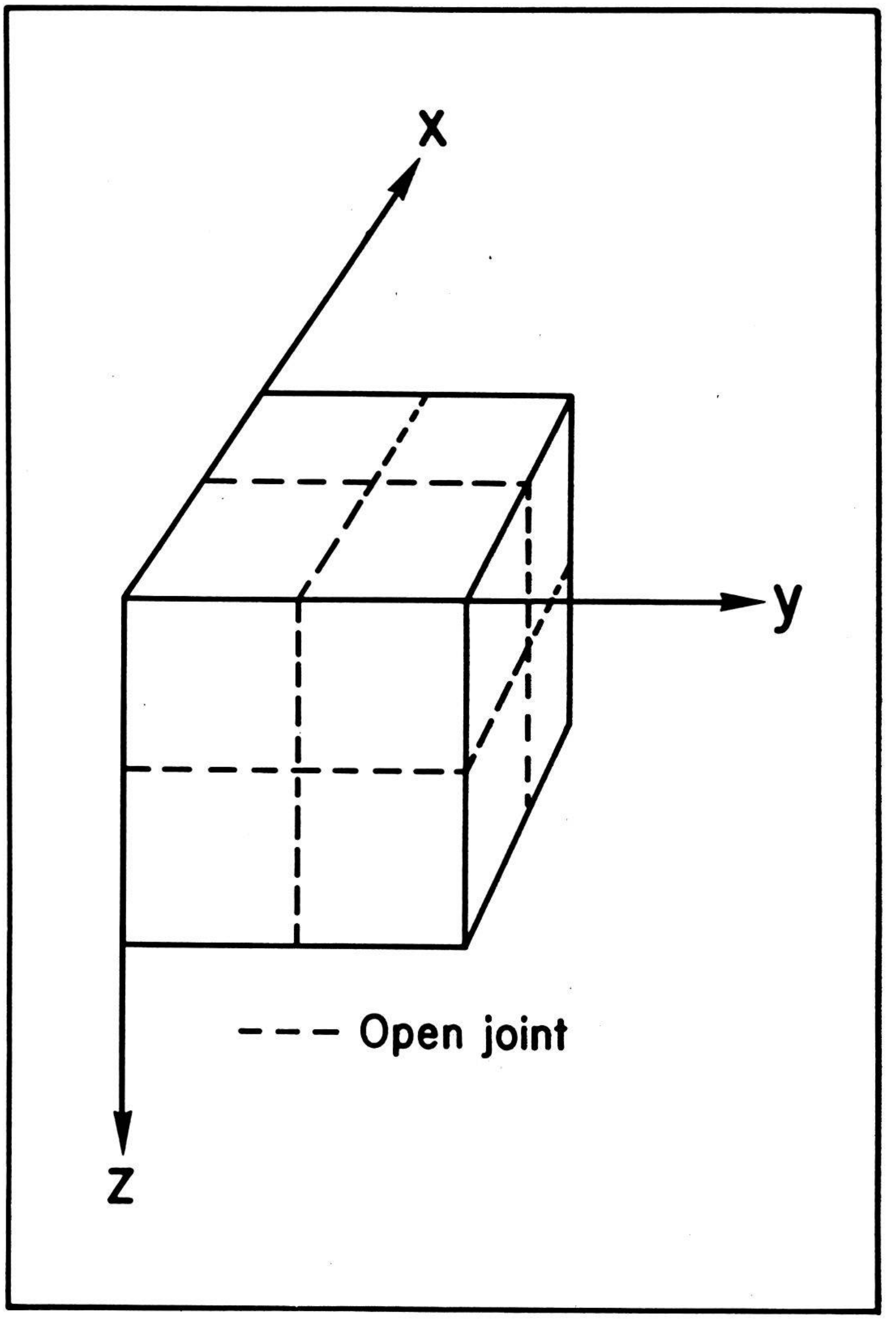

FIGURE 2
A simple scenario with three orthogonal fracture systems. Assuming a one metre lenght for the cube results in a fracture spacing (f_s) of one metre. Taking fracture width (f_w) as 1 mm produces the data shown in Table 1.

Before drawing any further conclusions we must address the oversimplification of this scenario. One may argue that the situation shown in Figure 2 is higly discriminatory insofar as it favours permeability over porosity. As shown the model assumes that fracture continuity (length) (f_c) exceeds the model dimension. This is equivalent to the assumption of an infinite fracture length without any necessity for the fluid flow to transfer between fractures and/or fracture sets. Fracture continuity introduces the concept of heterogeneity and in order to produce meaningful results, the model dimensions must be commensurate with the fracture heterogeneity. Pratically, that means that the model rock mass must be of similar size as the rock mass of interest. Figure 2 also rests on the assumption of the «flat crack» (called «cubic law» by some) and ignores fracture roughness (f_r). For the case where $f_r << f_w$ the model may still be appropriate provided one substitutes an apparent fracture width (f_w') of reduced size. In the case where $f_r \sim f_w$, the flow path will become tortuous and flow may no longer be laminar and the flat crack concept will overestimate fracture permeability (Δk_f). In contrast, the flat crack model does estimate fracture porosity (Δn_f) properly, provided one uses the mean width of a rough fracture.

These considerations may be summarized as follows:

$$\Delta k_f = f(\Sigma f_s, \Sigma f_w, f_c, f_r)$$

and

$$\Delta n_f = f(\Sigma f_s, \Sigma f_w)$$

where: Σf_s and Σf_w are the 3-dimensional fracture spacing and fracture width for the case with more than one set of open fractures.

Since the model of Figure 2 contains some silent and favourable assumptions in regard to f_c and f_r, it tends to overestimate the fracture permeability while correctly assessing the fracture porosity. Rather than make some fancy assumptions — usually based on little more than thin air — we arbitrarily reduce the computed permeability effect by two orders of magnitude to about 2 Darcies. In terms of hydrocarbon reservoir permeabiliy this is still a very large value. The earlier conclusion that joints affect permeability strongly while having little effect on the porosity is reaffirmed. From this follows the corollary that no reservoir can have appreciable fracture porosity without exhibiting excellent permeability. This factor was clearly realized by some of the early authors. Thus REGAN (1953) writes: «Fractured reservoirs are in general characterized by low porosity and high permeability». HUBBERT and WILLIS (1955) had this to say in regards to fractures: «... the porosity may be increased only slightly, but the permeability, because ist dependence upon size scale, may be increased enormously.»

The drastic effect of open fractures on fluid flow has nowhere been better demonstrated than in the process of «well fracing». The practice has been used extensively by the oil industry for over 30 years. This type of simulation technique may add well in excess of $100000 to a completion bill. The fact that this «in situ test» continues to be a commonly used procedure attests to its success in enhancing long range fluid flow. It more than any theoretical arguments lends credibility to the concept of fracture permeability.

In view of these facts the current emphasis on fracture porosity remains highly discomforting. It seems that despite the extensive literature on the subject there is still a basic misunderstanding lurking about. The «Glossary of Geology» (BATES & JACKSON, 1980) recognizes fracture porosity but not fracture permeability. The three texts on fractured reservoirs give fracture porosity an undue amount of attention. The basic and simple fact remains that any true fracture porosity of measurable proportions, say 2-5%, must be accompanied by a superpermeability. Claims to the contrary represent a basic contradiction indicating a fundamental misconception regarding reservoir properties.

In order for fractures to have an effect on fluid flow and storage these fractures must be open. One may argue that even in the case of tension fractures, subsequent closure will never be perfect because of the mismatch on opposite fracture walls due to minute lateral movements during opening. However, only the truly open fracture will have a measurable effect on permeability and porosity. Therefore, it becomes necessary to investigate the conditions required for open fractures in the subsurface. The many veined rocks are a mute testimony that such fractures at least temporarily exist regardless of any theoretical predictions. In terms of fluid flow a tightly filled (healed) fracture may in fact become a fluid barrier rather than a fluid conduit. Thus in the case of healed fractures the role of the fracture in terms of fluid flow may well be reversed.

4. Condition for open fractures in the subsurface

If fractures are to act as fluid conduits at least one set of these joints must be open. Across an open fracture no matrix stress can exist and it is thus mandatory that at least the smallest of the principal matrix stresses be zero. This can be achieved in two ways:

1. By superposition of bending or buckling stresses under conditions of active tectonism or by active release of the minimum lateral stress in an area of extension.
2. By increase of the pore fluid pressure to the point where at least the minimum total stress is completely carried by the fluid pressure.

One of the acknowledged fractured limestone reservoirs is that of Ain Zalah in Iraq (DUNNINGTON, 1958). Figure 3 shows a schematic cross section and gives the bending (assumed bending) stress on the outside of a beam according to JOHNSON (1970, p. 54). Clearly, it is not difficult to create the conditions for open

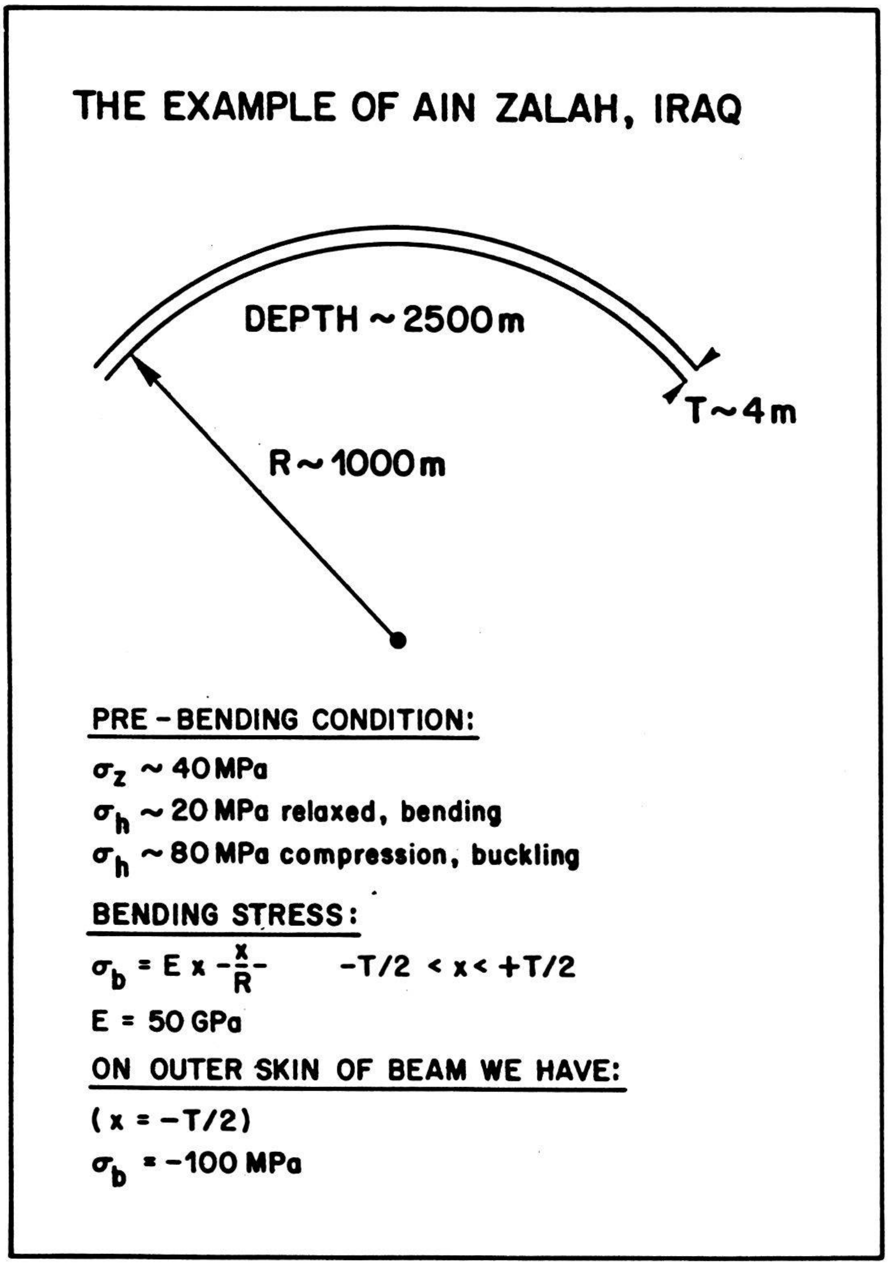

FIGURE 3
The bending stress on the outer skin of a beam 4 m thick in the example of the Ain Zalah reservoir, Iraq after DUNNINGTON (1958) and JOHNSON (1970). The message is clear: it is not difficult to produce tension cracks (joints) in the subsurface.

fractures. Since the tensile stress is restricted to the outer part of the individual beams, the fractured nature of a multi-beam reservoir may assume the interlaced nature shown in Figure 4. Permeability increase will be highest in both amount and vertical extent near the crest of the reservoir. Fluid flow in such a reservoir must be complex due to these vertical permeability alternations as well as pinchouts of the high permeability layers on the flanks. The importance of this pattern should not be lost on those attempting to maximize recovery from such a reservoir.

In areas of high formation pressure open fractures can be expected. When fluid pressure reaches its limiting value, i.e. is equal to the total overburden stress, the rock mass becomes totally destressed and a network of unoriented open fractures may exist leading to a uniform superpermeability. Such a case seems to exist in the Qum structure of Central Iran (MOSTOFI & GANSSER, 1957; GRETENER, 1982). Under conditions of less severe fluid overpressure individual sets of fractures may be open, leading to excellent but highly oriented (anisotropic) permeabilities.

Since geopressures occur in the form of wedges or lenses (GRETENER & FENG,1985) their effect on permeability is very similar to the one shown in Figure 4. Open fractures induced by geopressures will also not be vertically continuous but occur in distinct layers. These high permeability layers may be more extensive both laterally and vertically than shown in Figure 4. However, and this is most important, they, too, will not be vertically continuous. The very existence of geopressure is proof for this conclusion. Vertically continuous open fractures imply that the subsurface fluid system is uniform and open to the surface. Under such conditions only normal subsurface fluid pressures can prevail.

HUBBERT (1951) has shown that tension fractures, or zero minimum stress, can only be expected at shallow depth where the effective overburden stress is less than

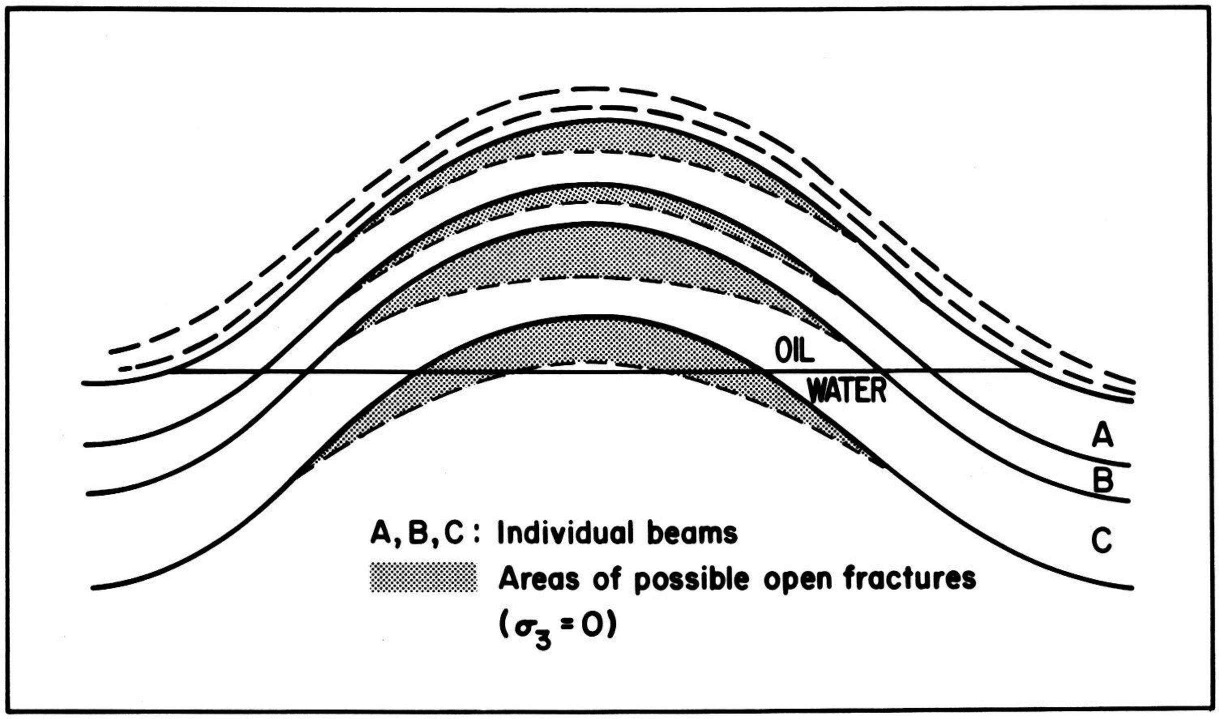

FIGURE 4 The expected distribution of fracture permeability and porosity in a multi-beam reservoir such as Ain Zalah. A real challenge to any EOR project.

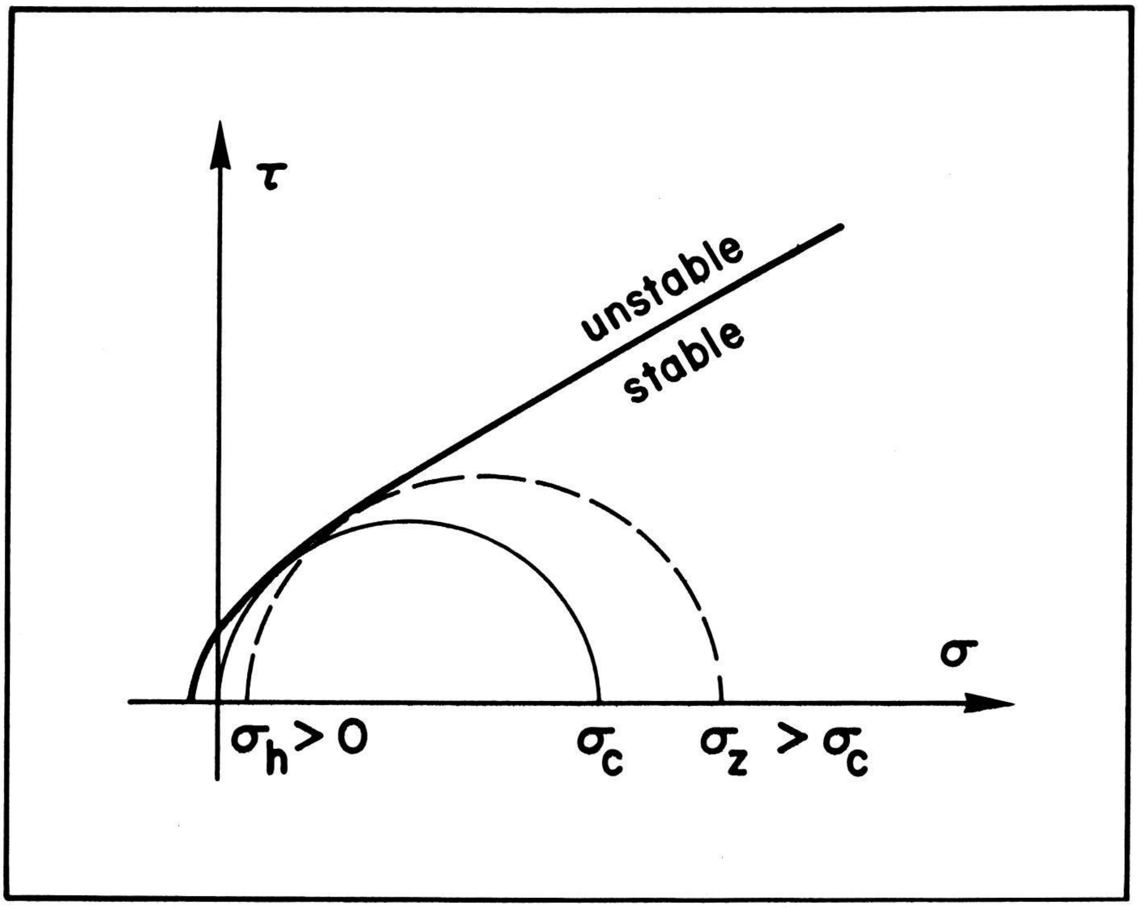

FIGURE 5 The concept of KING HUBBERT (1951): Where the effective overburden stress (σ_Z) exceeds the compressive strength of the rock (σ_C) the minimum horizontal stress cannot be relaxed to a zero value without prior failure in shear (dashed circle).

the compressive strength of the rock. The reasoning is shown in Figure 5. When the effective overburden stress (σ_Z) exceeds the compressive strength of the rock (σ_C), failure in shear will take place before the minimum stress reaches a value of zero (dashed circle in Figure 5). SECOR (1965) has shown that relief of the overburden stress due to abnormally high pore fluid pressures extends the «Hubbert Range» to essentially unlimited depths. Observations of open microcracks in the «Kola Well» at depths from 4.5 to 9 km provide direct confirmation for this postulate (KOZLOVSKY, 1984).

The compressive strength of rocks ranges from <70 MPa (<10,000 psi) to more than 250 MPa (35,000 psi). Under normal fluid pressure conditions the effective overburden stress gradient is about 14 MPa/km. Thus even without calling on abnormal fluid pressures, zero minimum stress can occur at depths ranging from 5 to 15 km, an ample range for the applied earth scientist.

SECOR (1965) stated that an increase of fluid pressure may under extreme conditions produce a negative (tensile) matrix stress within the rock and thus be directly responsible for the creation of fractures via the process of hydraulic fracturing. GRETENER and FENG (1985) have challenged this concept since the hydrofracing process depends on non-uniform fluid pressure. However, for the problem at hand there seems to be no disagreement on the fact that increasing fluid pressure will destress a rock and in the limit reduce all matrix stresses to zero.

As it goes unchallenged that pore pressure is affecting the matrix stress, pressure maintenance is always a primary concern in the presence of open fractures. Any drop in fluid pressure is liable to close at least some of the fractures, thus in effect «turning off the tap».

5. Identification of fractured reservoirs

None of the following criteria is infallible by itself, but a combination of these indicators may provide evidence for the existence of a fractured reservoir.

1. Under extreme conditions of fracturing bit behaviour during drilling may provide a clue to the nature of the reservoir (MOSTOFI & GANSSER, 1957, p. 83).
2. A low fracing gradient and concommitant lost circulation — not necessarily in the reservoir itself — may indicate conditions favorable for the presence of open fractures. Heavy mud losses may, however, not occur either due to quick sealing of the fractures by a mud cake, or by failure of the well to directly intersect the fracture system.
3. Open fractures can be suspected where such bulk reservoir examinations as pressure pulse testing, draw down testing, or history matches give permeability (and porosity) values higher than those obtained from core tests or log readings.
4. Open fractures may be detected by well-to-well seismic shooting, a survey method which at this time is in its infancy (BOIS et al., 1972; FEHLER, 1982).

6. Effect of open fractures on reservoir filling and depletion

The drastic, and not always beneficial, effect of open fractures on reservoir performance is best illustrated by the case of the Beaver River gas field in British Columbia, Canada (DAVIDSON & SNOWDON, 1978). This field was taken into production in 1971 at an initial rate of more than 200 MMcf/D with an estimated reserve in excess of 1 Tcf. In 1973 the production rate dropped dramatically to less than 60 MMcf/D and continued to decline. The field was shut-down in 1978 after producing only 178 Bcf. The postmortem revealed the following: In the presence of a two-system porosity the fractures were flushed of their gas by a strong water drive. Much of the matrix gas was left behind. In addition, it was found that in the matrix water saturation varied from 50 to more than 80% rather than the initially assumed, log derived, value of 25% (fracture water saturation 0%). The indicates that the fractures were present at the time of the gas accumulation and that trap filling was ineffective under those conditions.

There are lessons to be learned from this story:

1. Depletion of a two-system porosity reservoir must be handled with extreme care, particularly when the communication betweem the two systems is poor. Flushing of the fractures with accompanying isolation of the matrix-stored hydrocarbons is an ever present danger.
2. If the two-system porosity exists at the time of reservoir filling, the matrix porosity may never obtain a satisfactory degree of hydrocarbon saturation (the pro-

blem of depletion in reverse). The timing of the open fractures suddenly assumes great importance. Viewed in this context a late development of open fractures, post-dating the hydrocarbon accumulation, seems preferable.

3. A reservoir of the «Beaver River type» must be evaluated solely on the merits of its fracture permeability *and* porosity.

7. Artificial fracturing in reservoirs containing open fractures

Will artificial fracturing be beneficial in naturally fractured reservoirs? BLANTON (1982) stated the case as follows: «In fractured reservoirs constructive interaction with the natural fracture system is critical to the success of any stimulation treatment. To be most effective hydraulic fractures should cross and connect the natural fracture system...» In other words, the man-made fracture must tie the well to the natural plumbing system of the rock mass.

In a reservoir with a single set of open fractures these cracks will be oriented perpendicular to the minimum effective stress which must be zero. Theoretical considerations lead us to the conclusion that the artificial fracture must assume the same orientation. Thus it will extend parallel to the existing fractures and NOT provide the connection which is vital for a successful stimulation.

The answer to better production in such reservoirs is the *deviated* (preferably horizontal) *well.* Its azimuth must be parallel to the zero stress direction (usually horizontal) in order to provide optimum intersection of the existing fractures. This fact has already been recognized as shown by Elf's approach in such a case (ANON, 1984). Multiple fracturing of the horizontal well may be carried out to further enhance the rate of productin where necessary. The *parallel completion technique* followed (if necessary) by *hydraulic fracturing* is shown in Figure 6. It is advisable to run a four-arm dipmeter survey in the vertical hole in order to properly align the azimuth of the deviation. Well breakouts, if present, will provide the direction perpendicular to the open fracture set (GOUGH and BELL, 1981). It is my prediction that within 5 to 10 years the majority of oil/gas well completions will be of this type.

These theoretical considerations about well stimulation in fractured reservoirs were originally presented to the Canadian Society of Petroleum Geologists at a luncheon talk in October of 1982 and again at the regional spring meeting of the Society of Exploration Geophysicists in Denver in March of 1983 (GRETENER, 1983) The reaction was nil. The fact that this manuscript was delayed allows me to add the following highly comforting note. The crucial field, tests, fully confirming the above hypothesis, have been conducted in the Grassy Trail Field in Utah (ANON, 1986). The results of the described lateral completions verify my old maxim that good theoretical thinking, good laboratory experiments and good field observations never clash.

The Grassy Trail Field is producing from the Moenkopi Formation at a depth of 3,000 to 4,000 feet. The reservoir rocks are tight siltstones varying in thickness from 10 to 60 feet. The reservoirs containing fractures $^1/_2$ to $1^1/_2$ inches wide, spaced several tens of feet apart, are in essence a smaller version of the Gilsonite field (see section 2).

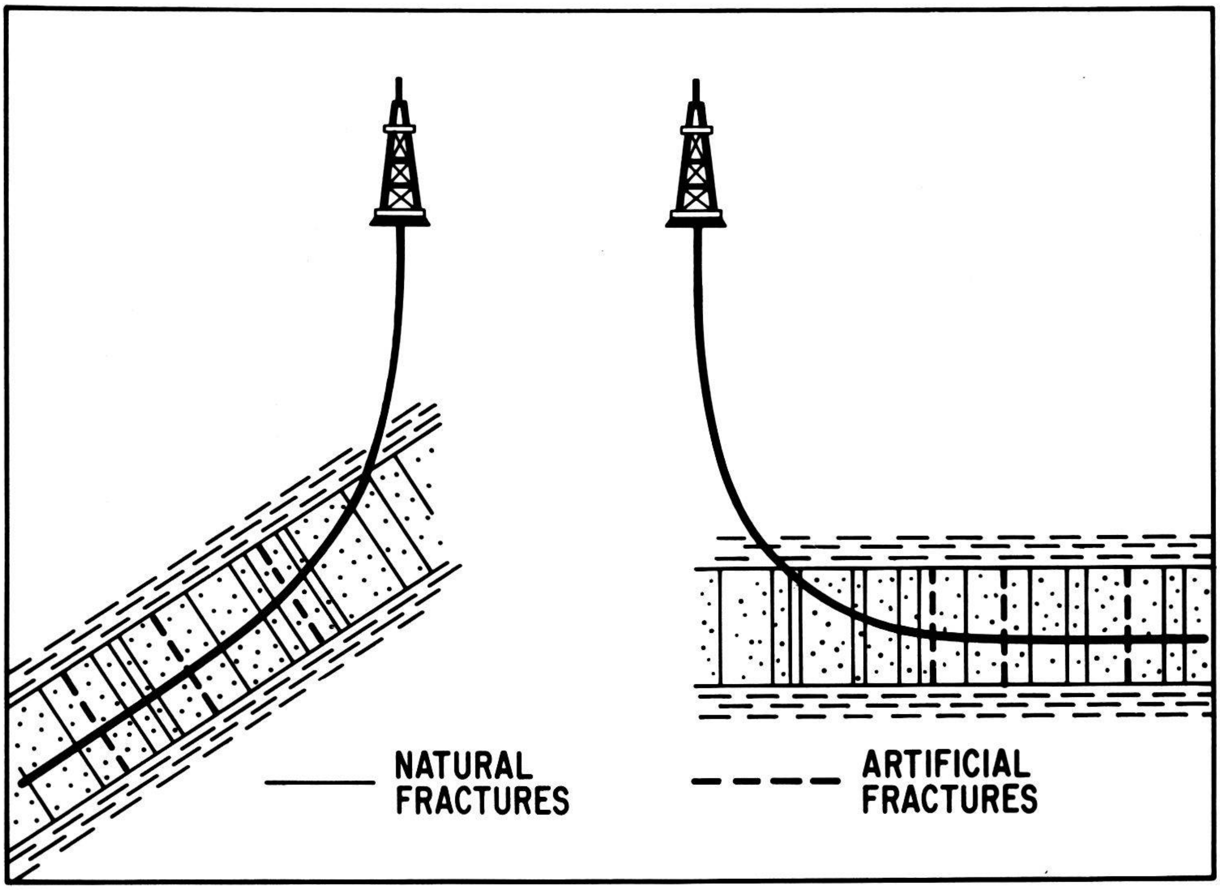

FIGURE 6 The parallel completion technique combined with subsequent hydraulic fracturing. The azimuth of the deviation must be perpendicular to the open fracture set. A superior type of completion in any reservoir where macrofractures affect the fluid flow.

A few quotes from the paper (ANON, 1986) suffice to make the point:

— «The field was producing oil from fractures and we thought the drainhole tool would allow the fractures to be intersected better than would conventional hydraulic fracturing.»

— «Tests indicated that hydraulic fracturing would not substantially increase production in the formations.»

— «Six of seven non-producing wells at the field became significant producers as a result of the lateral drilling.»

Amen!

8. Three minute summary

Field Observations:

1. Virtually no geological formation is free of discontinuities, in particular joint systems, whose origin in many cases is still obscure.
2. Joints often form very early, in fact during the transition from soil to rock. They also form at any time later whenever the proper conditions exist.
3. Tectonic deformation is not a necessary prerequisite for the formation of joints. This is not to say that such deformation will not create additional joint systems in accordance with the imposed stresses.

4. Tectonic deformation produces fracture patterns which are highly variable in intensity and orientation and which conform to the stress patterns inferred from the distortion of the rock mass.
5. Regional fracture patterns tend to have a larger fracture spacing and are uniform in orientation and spacing over large areas. Their origin is still obscure.
6. Carbonate rock masses are often characterized by «fracture clusters» whose origin remains yet to be explained.
7. The frequent occurrence of veins, particularly typical for carbonate rocks, attests to the fact that open joints in the subsurface are common, regardless of what «theoretical» considerations prevail.
8. The «Kola Well» shows the presence of open microcracks within the crust at depths between 4.5 and 9 km.
9. Low fracing gradients have been observed in connection with a number of fractured reservoirs.

General Observations:

1. For the hydrocarbon producer the joints vertical to sedimentary bedding are of particular interest.
2. Joints may be open, closed, or healed.
3. Fractures oriented perpendicular to bedding and thus paralleling the well axis are notoriously difficult to detect by current methods of well surveying.
4. Vertical joints tend to enhance both vertical and horizontal permeability. They tend to reduce the strong horizontal/vertical permeability anisotropy of sedimentary rocks.

Theoretical Observations:

1. In order for joints to have an effect on the storativity (porosity) of a rock formation at least one joint system must be open.
2. The condition of open joints in the subsurface requires that at least one principal stress be totally relaxed ($\sigma_3 = 0$).
3. Elementary considerations clearly demonstrate that open joints have a strong effect on the amount and directionality of the permeability but add little porosity.
4. Shear fractures, rather than tension joints, may provide fluid conduits even in loose, unconolidated reservoirs.

9. Conclusions

1. Open fractures are more common in the subsurface than current conventional wisdom would have it.
2. Such fractures play a crucial role in the fluid migration through rocks.
3. Fluid migration on a geological time scale is of critical importance for many types of diagenesis, the concentration of metallic ores, and the accumulation of hydrocarbons in traps.

4. The presence or absence, of open fractures is a crucial factor in reservoir management, and in particular, in any EOR concept.
5. Well stimulation by artificial fracturing is not likely to produce good results in reservoirs containing open fractures. The induced fracture will parallel the existing virgin open fracture system representing the natural plumbing system of the rock. Such fracturing will thus not provide the connection to the existing natural fluid conduits. The inclined well (horizontal, parallel to bedding and perpendicular to the open joints) is the answer.
6. Pressure maintenance is of utmost importance in hydrocarbon reservoirs containing open fractures. A pressure drop below a critical level may result in closing the fractures next to the well, thus shutting off the flow to the hole.

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List of symbols used for fracture description

f_c:	fracture continuity (length)
f_f:	fracture frequency ($f_f = 1/f_s$)
f_r:	fracture roughness
f_s:	fracture spacing
f_w:	fracture width
Σf_s, Σf_w:	refers to multiple fracture sets
Δk_f:	fracture permeability
Δn_f:	fracture porosity

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