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Autor: Gretener, P.E. / Guanjun, Zhao
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More on Fractured Hydrocarbon Reservoirs

11 figures and 5 tables

P.E. GRETENER[1] and ZHAO GUANJUN[2]

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Abstract

One dimensional stress relief leads to a single set of open fractures whereas multi dimensional stress relief produces two or more sets of open fractures. A single set of fractures results in a moderate fracture/matrix permeability contrast whereas for a multiset of fractures the same contrast is usually extreme. The Beaver River field fell victim to such a large permeability contrast.

Deviated or horizontal wells can usually be assumed to be mechanically stable within the reservoir. There is no reason not to revert to open-hole completions as recommended in this paper. It is the view of the authors that the parallel, open-hole completion is currently the best method for increased oil/gas recovery.

1 Department of Geology and Geophysics, University of Calgary, Calgary, Alberta T2N 1N4, Canada
2 Department of Petroleum Geology, Chengdu College of Geology, Chengdu, Sichuan, PRC

Zusammenfassung

Die eindimensionale Spannungsentlastung gibt Anlass zu einer einzelnen Schar von offenen Klüften. Die multidimensionale Spannungsentlastung produziert mehrere, nicht parallele Kluftscharen. Eine einzelne Kluftschar ergibt nur einen mässigen Unterschied in der Permeabilität zwischen Klüften und Gesteinsmasse. Für mehrere Kluftscharen ist derselbe Unterschied in der Regel extrem. Das Beaver River Feld wurde das Opfer eines solchen starken Permeabilitätsunterschiedes.

Man darf annehmen, dass abgewinkelte order horizontale Bohrlöcher im allgemeinen im Oelreservoir mechanisch stabil sind. In diesem Artikel empfehlen wir die Rückkehr zum unverrohrten Reservoiranschluss und dem steht prinzipiell nichts im Wege. Nach unserer Ansicht ist der Reservoiranschluss durch eine abgewinkelte (waagrechte), unverrohrte Bohrung zur Zeit die beste Methode für eine erhöhte Erdoelgewinnung.

THE NORTH AMERICAN (US/CAN) CONVENTIONAL OIL SITUATION From RIVA, 1988	
Produced	*142/13/155
Proved reserves	27/ 6/ 33
Inferred reserves & undiscovered resources	57/28/ 85
Total	226/47/273
* US/CAN/SUM in billion barrels	
To be discovered by exploration	85
Target for better recovery*	273
* doubling the current recovery factor of about 30%	

Table 1

1 Introduction

North America is a mature hydrocarbon producing area and currently highly dependent on offshore imports to meet its daily needs. New discoveries in this region will be largely small fields. A 10 million barrel discovery means great wealth for a small operator but only a one half day supply for the continent. RIVA (1988) describes the North American situation as shown in Table 1. Below the line are the inevitable conclusions one must draw from such an analysis. It clearly shows that the focus will shift from exploration towards the recovery factor and better exploitation of existing fields. This is not to say that exploration to the «last drop» should not also be pursued with great vigour. The shift is well under way as pointed out by FISHER (1987). During the period of 1979 to 1985 the dangerous decline of US reserves was essentially halted and FISHER (1987) states: «From 1979 through 1985, average annual reserve additions essentially matched production levels». Much of that favorable situation was achieved by extending the reserves of existing fields through infill drilling and other methods. It should not be forgotten that the North American situation is merely a forerunner of what is inevitably to happen to any hydrocarbon province.

For the benefit of the non-believers let us add the latest, two quotes from Larry FUNKHOUSER'S final Presidential Address in the AAPG EXPLORER of June 1988: «The U.S. government indifference to declining reserves and production is almost beyond comprehension. There is no question that vast resources of oil and gas remain to be found in the United States or to be coaxed out of known reservoirs through application of sound reservoir description practices», and «The resources that remain to be discovered and the even greater ones that occupy the EOR production realm can be realized only with intensive geologic study and innovation.»

In this context the internal nature of the reservoir assumes new importance. Better reservoir descriptions in terms of quantitative values for porosity and permeability are needed and found difficult to deliver. The terms RESERVOIR HETEROGENEITY and RESERVOIR ANISOTROPY are quickly gaining the status of buzz-words in the industriy, but without really coming into focus.

It is our contention that the almost universal presence and irregular distribution of open joints is a major source of both reservoir heterogeneity and anisotropy. The case for open fractures in the subsurface was made by GRETENER (1982 a; 1986) and the view seems to be gaining acceptance (BEAUMONT, 1986). It is also supported by the fact that no less than four textbooks on the subject have been published in the last decade (AGUILERA, 1980; REISS, 1980; VAN GOLF-RACHT, 1982; NELSON, 1985).

Our definition of the fractured reservoir may be a little broader than the generally accepted one. During depletion of a hydrocarbon reservoir a highly dynamic situation exists that exceeds any natural dynamic condition by several orders of magnitude. Our DEFINITION OF THE FRACTURED RESERVOIR reads: «A HYDROCARBON RESERVOIR WHERE OPEN FRACTURES SIGNIFICANTLY AFFECT THE FLUID FLOW DURING THE DEPLETION PROCESS». For this definition we stand by our previous statement: «There is no such thing as an unfractured reservoir». (GRETENER, 1982 a).

Figure 1 represents an attempt to classify any geological feature that even remotely could be called a fractured reservoir in terms of fracture spacing (fs) and fracture width (fw). On the abscissa the fracture spacing is plotted and on the ordinate the fracture permeability reduced by a factor 10 to make some allowance for fracture roughness and discontinuity. The Grassy Trail field (ANON, 1986) and the Gilsonite dikes of Colorado/Utah (DAVIS, 1957) represent stages intermediate between the classical fractured fields of the oilpatch and the mafic dike swarms found in old shield areas. The dike material ranges from basalt to gilsonite (solid bitumen) to heavy oil to conventional oil and gas. Some is now solid some still fluid but the emplacement mechanism in all cases is the same. Pure and applied geology are often much closer together many would like to think.

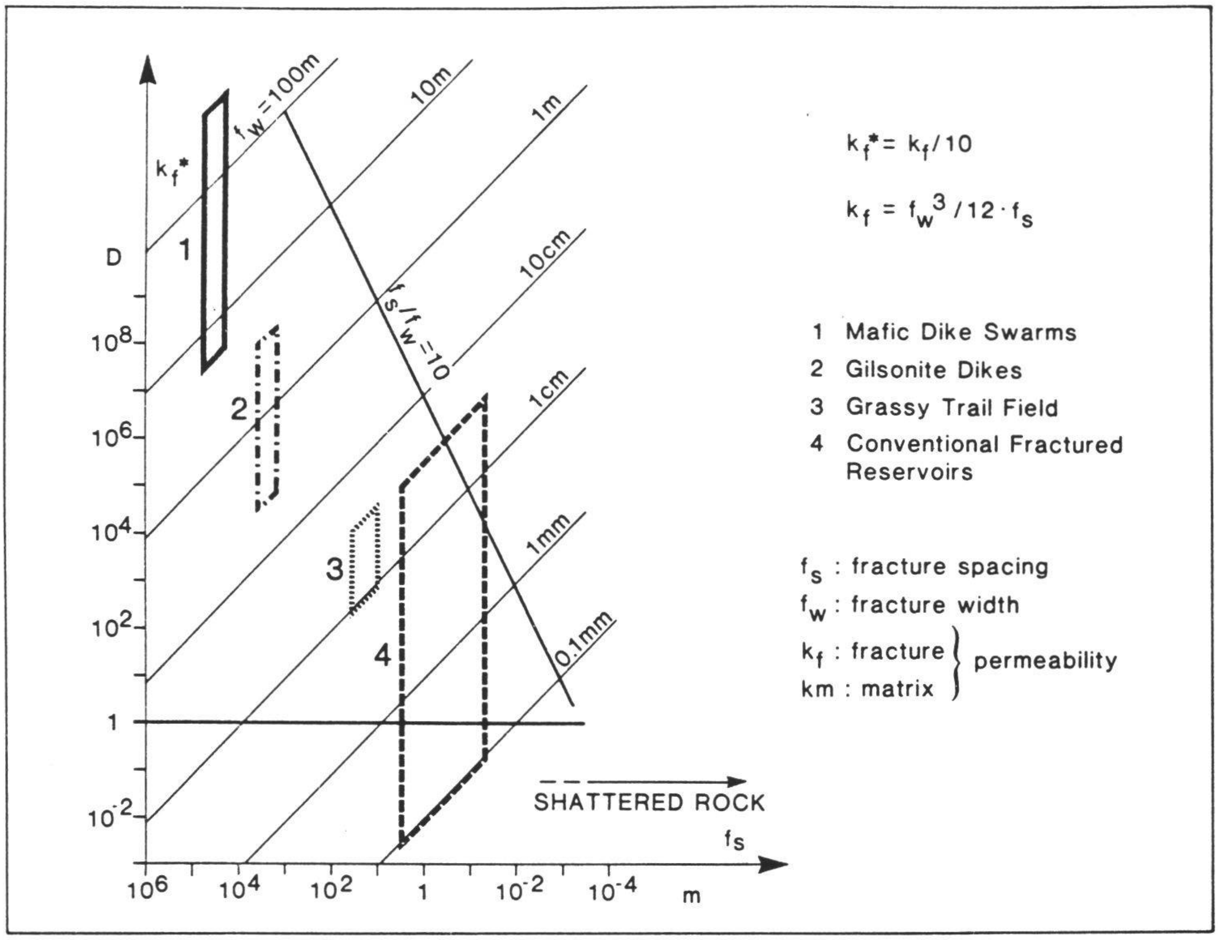

Fig. 1 An attempt to classify in terms of fracture spacing (fs) and fracture width (fw) all geological features that might qualify as fractured reservoirs.

The present paper is a continuation of an earlier paper (GRETENER, 1986). We investigate in the following some of the points which were only given a cursory examination and we also pursue some of the questions raised but left unanswered. For the sake of brevity this earlier paper (GRETENER, 1986) will be referred to as the «previous paper» throughout this text.

2 On Stress Relief

Many geologists did, and do, consider the occurrence of open fractures in the subsurface an unlikely phenomenon. The reason against such a postulate runs as follows: As one progresses into the earth the effective compressive stresses will increase. An open fracture requires that the effective stress normal to such an opening be completely relaxed.

This line of reasoning can be attacked along two lines:

1. It can be shown that rock deformation can locally relieve the regional stress and thus permit the occurrence of open fractures in selected areas.
2. It can be questioned whether zero normal stress is truly a requirement for a fracture to act as a fluid conduit.

In this section it is our intent to demonstrate that fractures acting as fluid conduits can be present to great depths.

As ANDERSON (1951) has postulated, and later measurements have confirmed, the normal subsurface stress configuration is for one effective principal stress to be vertical and the other two to be horizontal. thus we have: σ_Z, σ_H, and σ_h, where $\sigma_H > \sigma_h$. Stress relief can assume the following forms:

one dimensional 1-D : $\sigma_1 > \sigma_2 > \sigma_3 = 0$

two dimensional 2-D : $\sigma_1 > \sigma_2 = \sigma_3 = 0$

three dimensional 3-D : $\sigma_1 = \sigma_2 = \sigma_3 = 0$

One must remember that the subscripts 1,2,3 and z, H, h are freely interchangeable depending on the tectonic environment (compressional, extensional, or relaxed).
The requirement of zero stress for open fractures will allow for one set of open fractures under the condition of 1-D stress relief. This is no doubt the most common condition encountered in practice. 2-D stress relief permits two orthogonal sets of open fractures and 3-D (total) stress relief permits a network of unoriented open fractures such as may be observed in a stoping magma.

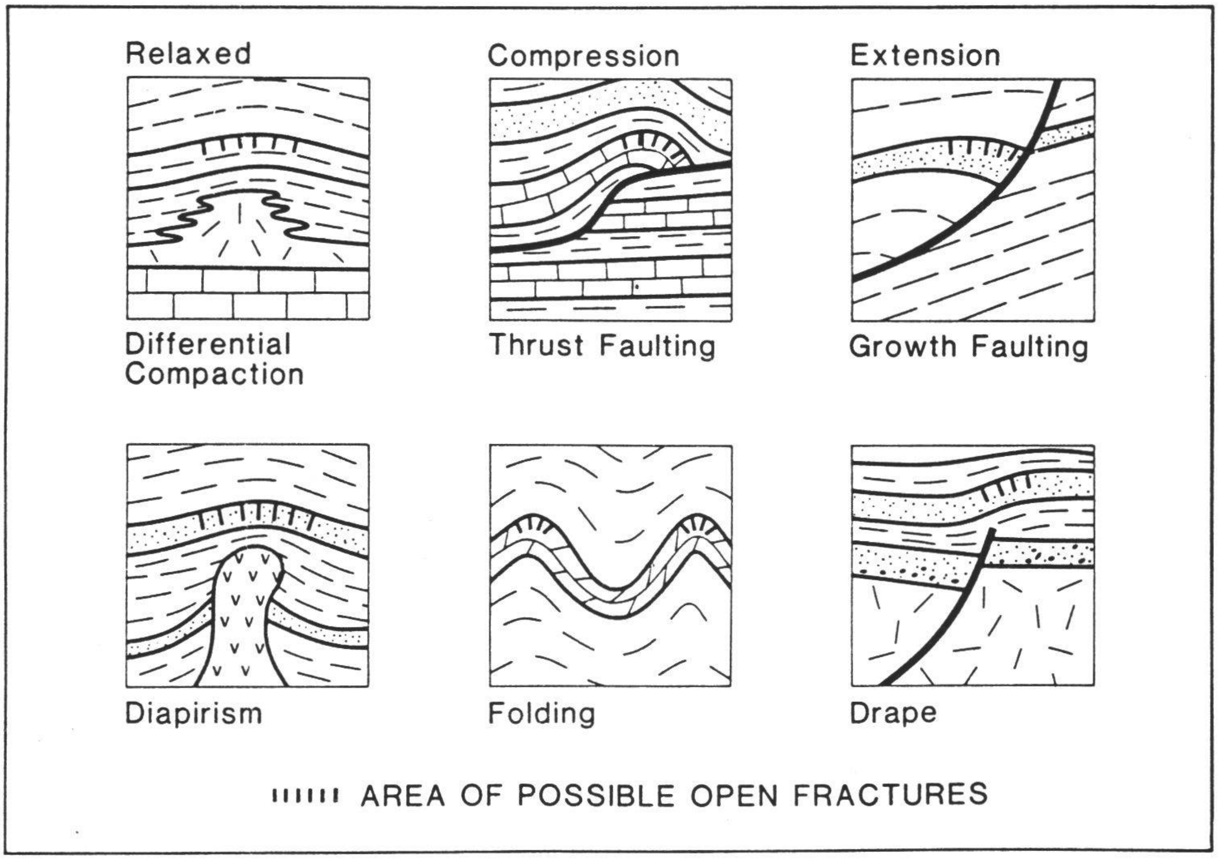

Fig. 2 Geological situations where local stress relief can be expected.

TYPES OF STRESS RELIEF IN VARIOUS TECTONIC SETTINGS

1-D Stress Relief	2-D Stress Relief	3-D Stress Relief
BENDING ON ROLL-OVER OF GROWTH FAULTS (E)	BENDING OVER A SALT OR SHALE DIAPIR (E,C,R)	HARD GEOPRESSURE WITH $p \cong S_z$ (OVERBURDEN IN FLOATATION)
DRAPING OVER DEEP-SEATED (BASEMENT) FAULTS (E)	DIFFERENTIAL COMPACTION OVER PANCAKE* REEFS (R)	
BENDING OVER RAMPS OF THURST FAULTS (C)	BENDING IN STEEPLY DOUBLE PLUNGING ANTICLINE (C)	
BUCKLING IN FOLDED STRATA (C)	BENDING OVER 3-D SALT COLLAPSE (R)	(E) EXTENSION
BENDING DUE TO DIFFEREN-TIAL COMPACTION OVER A SHALE-OUT EDGE (R)	VOLUME SHRINKAGE: MUD-CRACKS, COLUMNAR JOINT-ING (E,C,R)	(C) COMPRESSION (R) RELAXED
BENDING OVER 2-D SALT COLLAPSE EDGE (R)		

* there is no such thing as a pinnacle reef!

Table 2

Table 2 and Figure 2 give an overview of the types of stress relief that one can expect in various tectonic environments. It is immediately obvious that the popular «sugar cube» model must be labelled a curiosity that will only be encountered under rare conditions. One of these may well be the Alborz structure in Central Iran (GRETENER, 1982 b). The sugar cube model contains three orthogonal sets of open fractures. The fractures are viewed as smooth, flat cracks of infinite length. One crack per square metre with a width of 0.1 mm leads to a fracture permeability of 80 mD. For the sugar cube model this results in a permeability increase of 160 mD in all directions and a porosity increase of 0.03%. As stated in the previous paper, fractures enhance permeability enormously while adding little porosity, a fact well known to the early researchers in this field (REGAN, 1953; HUBBERT & WILLIS, 1955).

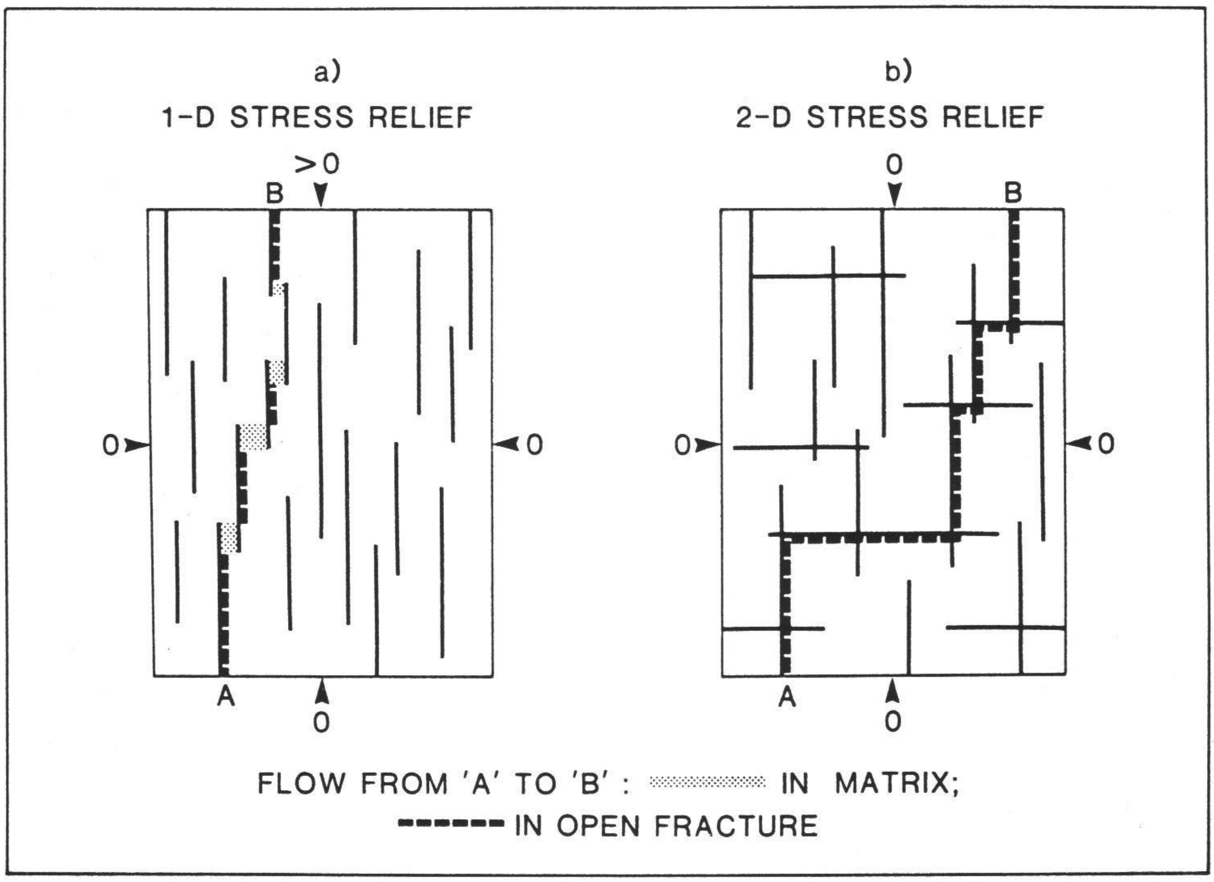

Fig. 3 1-D and 2-D stress relief, the resulting open fracture pattern, and the fluid flow paths.

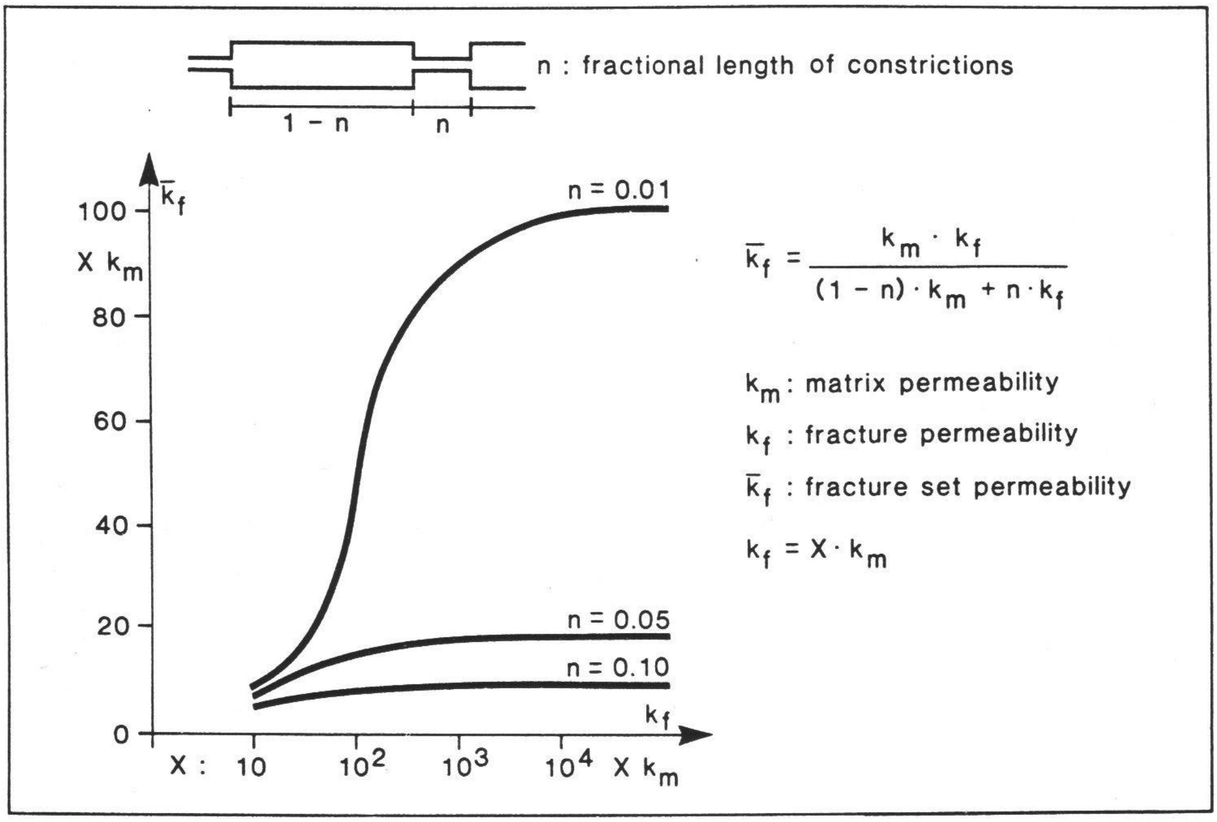

Fig. 4 Fracture permeability (kf) versus matrix permeability (km) for the one-set fracture system that acts as a pipeline with constrictions.

There is a fundamental difference between the one-set fracture system and the multi-set fracture systems. In the former the fluid flow through the rock mass must transfer from fracture to fracture via the matrix, due to the finite fracture length (not considered by the sugar cube model). In the multi-fracture system any flow direction can be assumed by following open fractures and only slightly lengthening the flow path. Thus 2-D and 3-D stress relief, that produce multi-set fracture systems, result in great fracture/matrix permeability contrasts as predicted by the sugar cube model. As we shall find out later this may be undesirable (section 7). The one-set fracture system acts as a pipeline with constrictions. Due to the limited length of the individual fractures the fluid must transfer by way of the matrix from fracture to fracture as shown in Figure 3a. In contrast to the two-set fracture system of Figure 3b the fracture/matrix permeability contrast is greatly reduced. In the case of Figure 3a the permeability contrast is not likely to exceed two orders of magnitude as shown in Figure 4. For multi-set fracture systems this contrast can easily assume four orders of magnitude as indicated by the sugar cube model. This can be a detrimental aspect not allowing for an interaction between the matrix and the fracture fluids during the highly dynamic depletion phase. Only in the conventional fractures-only reservoir where fractures provide both fluid conduits and fluid storage is a fracture superpermeability a glorious event. HALDORSEN (1986) has shown how permeability decreases as the model dimensions exceed the fracture length.

We must now address the second question whether it is really necessary to reduce the stress across a fracture to zero in order for it to act as a fluid conduit. The experiments of TSANG & WITHERSPOON (1981) indicate that a normal effective stress of less than 2 MPa (300 psi) brings about a very drastic reduction of fracture permeability. However, these are the results from tests on small laboratory samples which cannot be directly applied to fracture surfaces which measure tens or hundreds of square metres. This suspicion is nurtured by observations in tunnels and mine adits in basement rocks where fractures provide the only avenues for fluid flow. Large influxes of water have been encountered when cutting into fracture zones. In many cases there is no evidence of perfect stress relief. Observations in the Kola Well (KOZLOVSKY, ed., 1987), suggest open fractures at a depth of up to 9 km. In the Siljan well open fractures were encountered at a depth exceeding 6 km (ANON, 1987). Experiments on crystalline rocks indicate that a normal stress of about 30 MPa (4500 psi) is required before a strong decrease in permeability is observed (KOZLOVSKI, ed., 1987, p. 337). One may explain these observations by reasoning that complete closure of a fracture is never likely, due to minute misalignments of the opposite walls during opening and due to subsequent channelling, a process similar to piping, that tends to further erode the fracture surface (analogous to acidizing artificial fractures).

Clearly it is not possible at this time to draw any final conclusion in regards to stress relief. However it seems fair to state that stress relief — not necessarily to zero level — promotes fracture permeability and that the evidence for such permeability in the subsurface is convincing.

3 Geological Provinces where open fractures can be expected

An examination of Figure 2 shows that open fractures can be expected anywhere. No tectonic environment is exempt. It is important to note, however, that generally stress relief will be limited to specific areas and it will not be all pervasive. This means that the resulting open fractures will not only enhance reservoir anisotropy but equally contribute to reservoir heterogeneity. About the only exception to this rule is the 3-D stress relief caused by hard geopressures. Such situations are often, though not always, widespread. The whole reservoir may be affected and have a reasonably uniform high fracture permeability and porosity.

Also noteworthy is the following fact. Most often stress relief of the 1-D type is provided by bending. In an extensional environment (growth faulting on continental margins) it is the smallest principal stress ($\sigma_h = \sigma_3$) that is relaxed whereas in a compressional province (folding, thrust faulting) the maximum compressive ($\sigma_H = \sigma_1$) is reduced. This is a factor that will have to be taken into consideration in section 4 where the stability of the horizontal well is under investigation.

We find that the idea of the fractured reservoir as defined in this paper is relevant to the explorationist and reservoir engineer regardless of where their field of operation is located.

4 On Lithohydraulic Units

In the early days of hydrocarbon exploration the term «reservoir description» mainly referred to the external geometry and the total volume of the reservoirs. The internal complexities of the reservoir were handled by assigning average porosity and permeability values for the whole reservoir. It need not be stressed that this procedure will no longer suffice for the optimum exploitation (WEBER, 1986). It is now clear that at least semi-detailed descriptions of the internal reservoir compartments are badly needed. It has become painfully obvious that the variations of the physical properties existing within most reservoirs have been badly underestimated.

The term «depositional environments» is currently a great favorite of petroleum geologists. However, unless translated into reasonable uniform bodies of porosity and permeability the term will not impress reservoir engineers. KRAUSE ET AL. (1987) have recently coined the term «lithohydraulic units». The question yet to be solved is the extent to which such units will conform to depositional environment units. Any initial correlation that may exist may later be obscured by diagenetic processes and by crosscutting fractures. Fracturing may well eliminate or reduce the effectiveness such flow barriers as clay drapes or shale laminae.

The term «lateral continuity» has also moved into the limelight. Two units of high porosity and permeability are encountered in neighbouring wells at about the same depth. Are these two separate lenses or one continuous unit? This question relates to what MCGUGAN (1965) has called the persistence factor. It is one task of outcrop studies to establish the persistence factor (lateral continuity) for various lithohydraulic units. Subsurface geology, based on well information, is subject to the severe limitations of digital sampling. No amount of logging can remove the fact that the sample rate even in a developed field is woefully inadequate (40 acre spacing leads to a well distance of 1300 ft, 400 m).

The only hope for in situ reservoir descriptions lies with the geophysicists. Tomography, shear wave studies, large offset VSP surveys (NOBLE ET AL., 1988) improved surface velocity analysis and others may prove useful. Outcrop studies (HINRICHS ET AL., 1986; MIALL, 1988) can provide guidelines as suggested above but cannot forecast the precise location of either permeability barriers or conduits within a given reservoir.

For some years to come we will not have the detailed guidance needed and in fact we may never have it since it is not sure that the above mentioned geophysical methods will have sufficient resolution. What then is there to do? As pointed out in the previous paper: «lengthen the well path in the producing section — the parallel completion (horizontal well)». It was stated that within 5 to 10 years the majority of the conventional oil completions would be of this type. This may be viewed as an optimistic forecast by many but a scanning of the Petroleum Abstracts and papers currently appearing in the trade journals (ANON, 1984; SHIRLEY, 1986; PETZET, 1988) indicate that we are well on the way to achieving this goal.

5 On the Near-Well Permeability

Flow velocities around a producing, vertical well will increase linearly as the well is approached due to cylindrical crowding. Thus for a 20 cm (8 in) well the seepage velocity at the bore hole wall may be in the order of 500 m/d (1500 ft/d) for a good producer. At a distance of 1 m (3 ft) it will be 50 m/d (150 ft/d) and at 10 m (30 ft) it will be 5 m/d or (15 ft/d). Note that all these distances are negligible in comparison to the well spacing even in a fully developed field. Clearly the permeability in the IMMEDIATE vicinity of the well dictates the well-efficiency. This is true for both withdrawal and injection, be that groundwater, oil, gas, or liquid waste.

The idea has been known to the water-well drillers for a long time. A gravel lens of limited extent within a sand or silt body is all that is needed to turn a marginal or unecono-

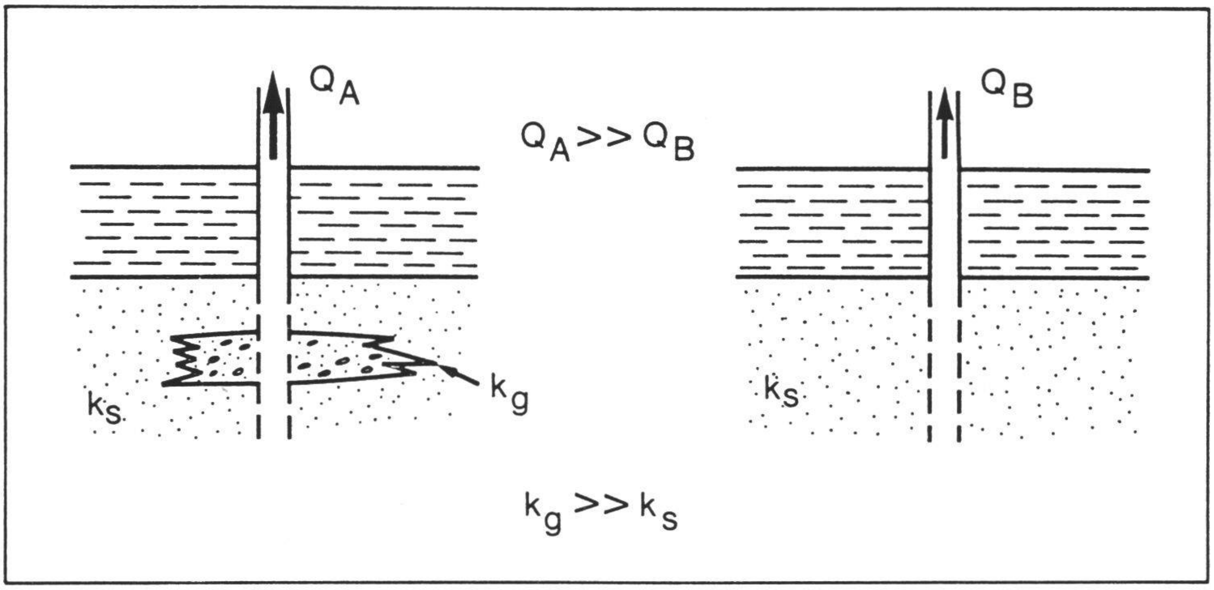

Fig.5 The effect of a limited gravel lens on well productivity. The section of higher near-well permeability suffices to improve productivity dramatically.

mic producer into a satisfactory supplier of groundwater. The concept is shown in Figure 5. The importance of the near-well permeability is equally well appreciated by the reservoir engineers of the oil patch who have addressed this problem extensively under the name of FORMATION DAMAGE. In this case the natural permeability is unfavourably affected by the drilling process with often disastrous results.

Reservoir heterogeneity is now recognized as being far more severe than previously thought. Thus most reservoirs are a mixture of compartments with poor, good, and excellent permeability. Neither the size, nor the distribution nor the geometry of these compartments is very clearly understood in many cases. Well productivity in most fields is highly variable (see e.g. SANFORD, 1970, p. 474). A good producer will — by accident or design — cut one of the high permeability compartments. MCQUILLAN (1985) shows how variations in the matrix porosity and fracture density affect well productivity in the Bibi Hakimeh field (Zagros Mtns., Iran). We must thus accept the fact that there exists a phenonemon which, for the lack of a better word, we may call NATURAL FORMATION DAMAGE: the fact that a well, just by chance, may not intersect any of the better permeability areas.

The question remains as to what to do under current circumstances. As far as reservoir heterogeneity is concerned the state-of-the-art is much ignorance and little hard facts, except that variations are severe and occur on all scales (HINRICHS ET AL., 1986). Under those conditions extending the well path in the productive interval is the unsophisticated answer. The deviated or horizontal well, with the azimuth chosen wisely, is the best way to combat both directional and random reservoir heterogeneity and assure that a stretch of improved near-well permeability is in contact with the well.

6 New Completion Practices — Stability of Horizontal Well

In sections 4 and 5 we have suggested that lengthening the well path through the producing interval will alleviate production problems caused by the natural heterogeneity and anisotropy of the reservoir. Such practice calls for drilling the deviated or horizontal well. The azimuth of such wells must be oriented in such a way as to intersect possible open, vertical fractures.

There are two different methods to obtain a horizontal well. One is conventional deviated drilling with a medium turning radius (150 m, 500 ft) with traditional equipment (ANON, 1988). In that manner wells have been drilled with horizontal sections up to 500 m (2000 ft) long. These wells can be logged, cased, fractured and in any way treated like a normal well (SPREUX ET AL., 1988) at increased but competitive costs (BOSIO & REISS, 1988). Another method uses the drainhole technology (GORODY, 1984). By ways of special equipment (hinged drill collars) a well is turned from vertical to horizontal in a distance of about 10 m (30 ft) and horizontal sections up to 200 m (700 ft) in length can be drilled. As far as we know such drainholes cannot be treated extensively and must at this time be left as open-hole completions. According to latest reports (EMERY, 1988) they have, however, been fractured.

In drilling horizontal wells in order to intersect vertical, open fractures the azimuthal control is not critical. A deviation of 20° from the optimum direction will only increase the apparent fracture spacing by 6%. The optimum direction for the case of two fracture sets may be found using the method described by NOLEN-HOEKSEMA and HOWARD (1987). However, in view of the expected high fracture permeability (section 2) the azimuthal orientation will not be crucial. Vertical control, however, must be very accurate particularly in places with thin hydrocarbon columns.

The technology now exists to drill accurately horizontal completions of different types. In view of the extreme reservoir heterogeneity we must also review our preferred completion through perforations. This practice no doubt appeals to engineers since it is clinically clean providing us with a well that promises to function for years to come with no problems. However, perforations further concentrate and accelerate the near-well flow. They also provide only spotty access to the formation and cannot be placed optimally in terms of formation heterogeneity. It seems high time to review the resurrection of the barefoot completion which in terms of reservoir heterogeneity is least sensitive, else much of the advantage gained by the lengthened well path may be lost again.

If the open hole completion is to be seriously contemplated the mechanical stability of the horizontal well must be looked at. In a vertical well spalling is an undesirable process which may lead to drilling and completion problems. In the end, however, the vertical well is self-cleaning which is certainly not the case for the horizontal well. Thus the question is very real: «Can we afford an open hole completion in a horizontal well, and is it worthwhile to drill a drainhole that cannot be cased?».

We must remember that the horizontal portion of our completion will be located in a reservoir rock. Such rocks tend to be strong (there are a few exceptions) and are usually not the main offenders in areas where well stability is a problem. It is generally the weak shales that are subject to spalling and caving. Failure occurs in response to a high tangential stress at the borehole wall which is caused by a large difference between the virgin radial stresses. In the case of a horizontal well the latter will be the effective overburden stress and one of the principal horizontal stresses.

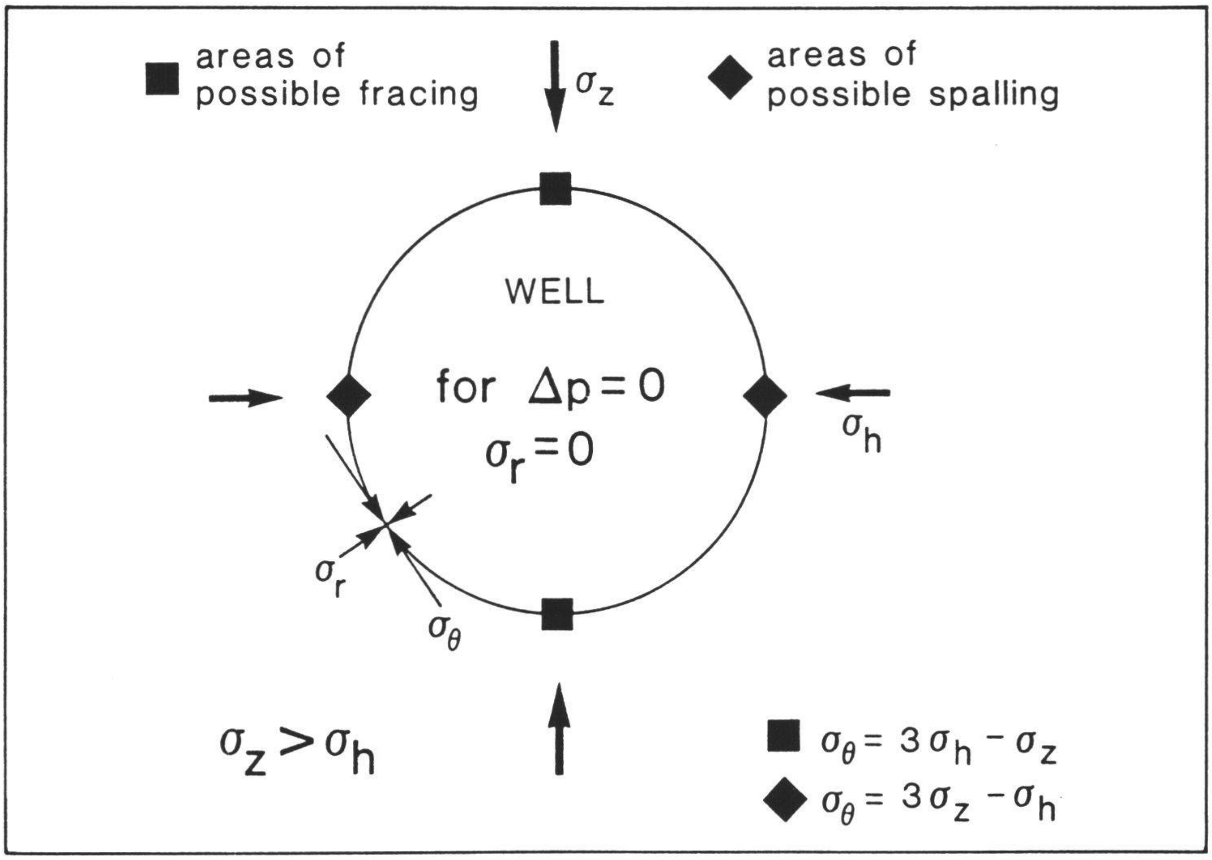

Fig. 6 The stresses at the borehole wall induced by the virgin rock stresses.

Figure 6 shows the principal stress concentrations at the wall of a horizontal well as induced by the virgin rock stresses. One must recall that the least principal stress at the borehole wall, the radial stress (σ_r), will be zero under conditions of production (no overbalance).
Thus failure in shear is possible at the points of maximum tangential stress ($\sigma_{\theta max}$). For stability it is necessary:

$$\sigma_{\theta max} < \sigma_c$$

where: σ_c = compressive strength of reservoir rock, since $\sigma_r = \sigma_3 = 0$.

In fairness it must be pointed out that at this time there is still some discussion about the exact failure mechanism that leads to spalling (DEY & KRANZ, 1988). In our further investigation we adhere to the prevailing view of failure in shear.

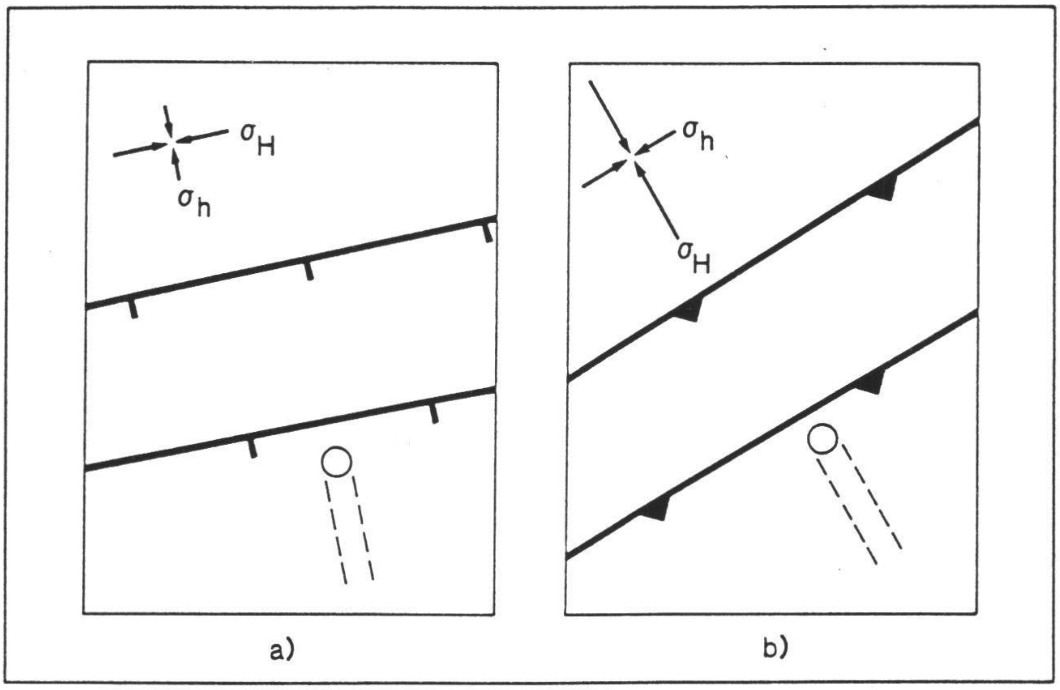

Fig. 7 a) The orientation of the optimum well deviation in an extensional area.
b) The orientation of the optimum well deviation in a compressional area.

The azimuthal orientation of a horizontal well will usually be such that any possible open joints will be intercepted by the well. In the case of an extensional province it is the least horizontal stress that is relieved by bending through the roll-over (Figure 7a) and in the case of a compressional province it is the maximum horizontal stress that is relieved by bending over thrust-ramps resulting in a well orientation as shown in Figure 7b. In a relaxed area the 4-arm dipmeter (caliper) log will provide the orientation of the breakouts which in turn give the direction of the minimum and maximum horizontal stresses (GOUGH & BELL, 1981). The maximum tangential stress on a horizontal well is thus:

EXTENSION	COMPRESSION*	RELAXED
$\sigma_{\theta max} = 3\sigma_z - \sigma_H$	$\sigma_{\theta max} = 3\sigma_z - \sigma_h$	$\sigma_{\theta max} = 3\sigma_z - \sigma_H$

* usually in the present areas of exploration there is no evidence of active faulting. A case of remanent compression where the least compressive horizontal stress is relaxed to the point where it is lower than the overburden stress (FORDJOR ET AL., 1983, p. 1451, Fig. 6).

In all the above cases one can say that the horizontal stress will be equal to or smaller than the overburden stress and generally range from 0.5 to $1.0.\sigma_Z$.

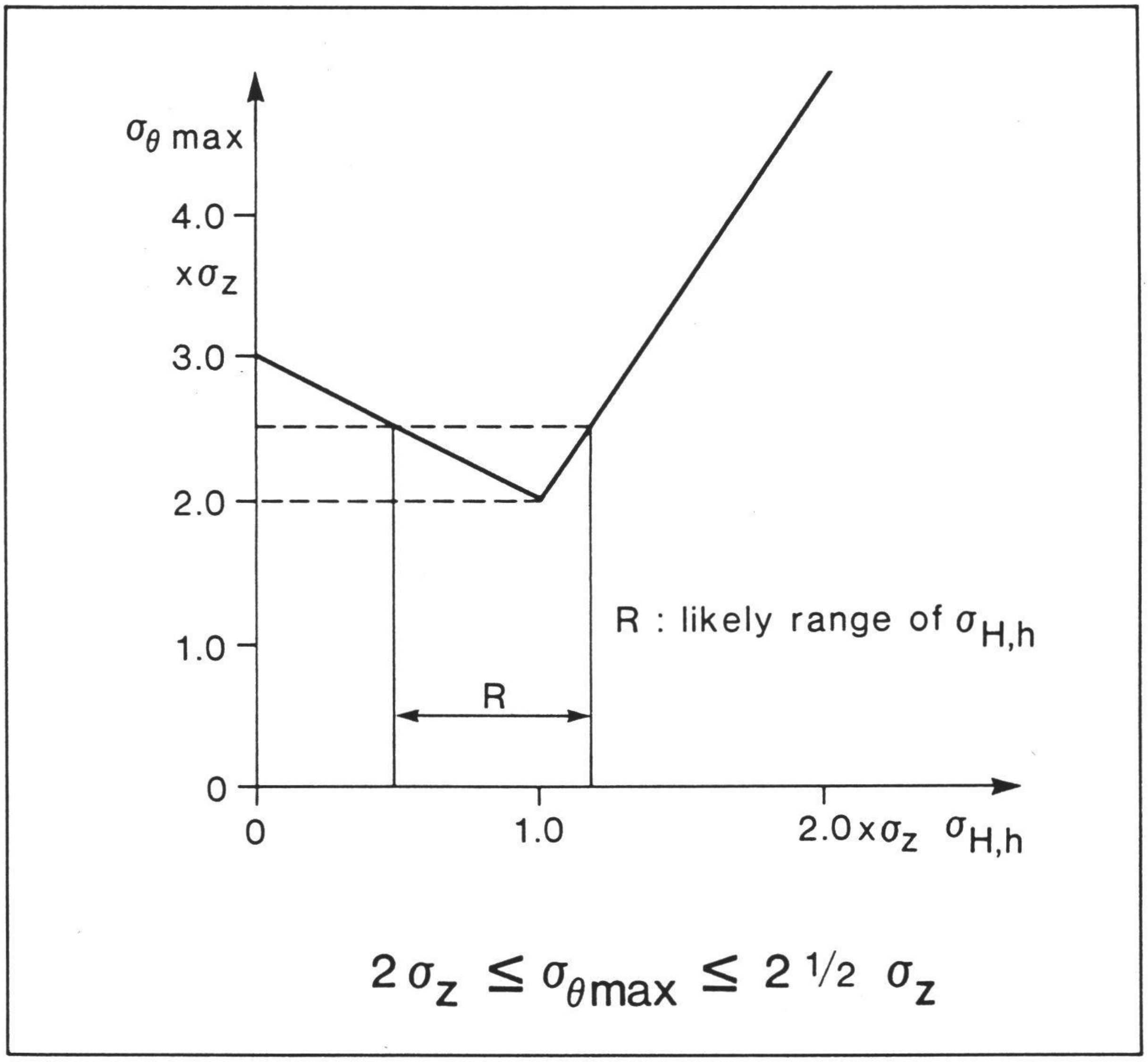

Fig. 8 The maximum tangential stress at the wall of the horizontal well as a function of the virgin horizontal and vertical stresses.

From this it follows that the maximum tangential stress ranges from about 2 to $2^1/_2.\sigma_Z$ (Figure 8). Under normal pore pressure conditions the effective vertical stress increases at about 13 MPa/km (0.6 psi/ft). The compressive strength of reservoir rocks range from 40 to over 200 MPa (6000 to 30,000 psi). Possible corrections for the size factor (KOSTAK & BIELENSTEIN, 1971) would be negligible since the rock volume affected by spalling is small. Using those numbers it is possible to construct Figure 9. It provides a guide-linie for well bore stability. The indication is that normal strength reservoir rocks are stable to a depth of 3-4 km (10,000 to 13,000 ft), high and very high strength rocks can be assumed to be stable to a depth greater than 5 km (17,000 ft). Only weak and very weak rocks have a depth limit of about 2 km (7000 ft). The general conclusion follows that open hole completions of horizontal wells should not meet with difficulties except in cases of extreme depth or very low strength reservoir rocks.

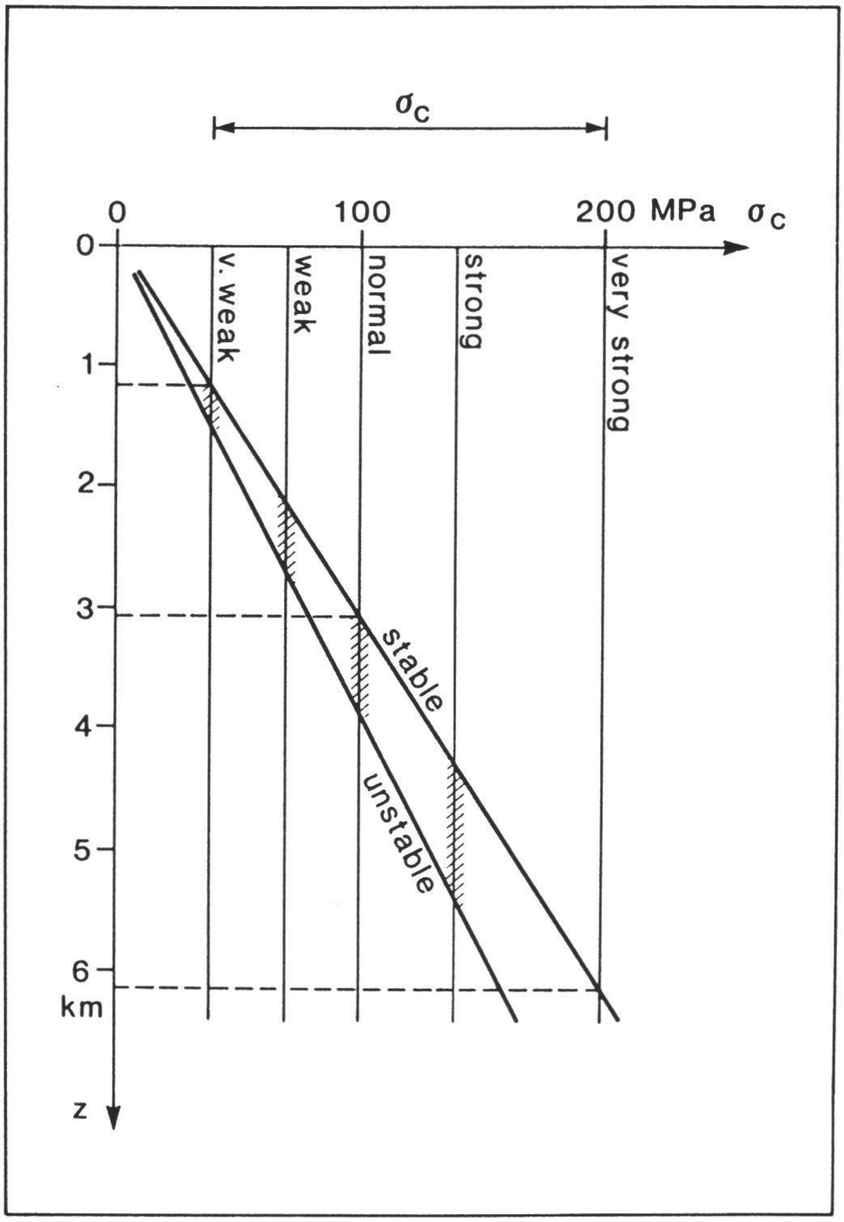

Fig. 9 The stable depth realm of the horizontal well as a function of the compressive strength (σc) of the reservoir rock.

Some engineers may find the above analysis mildly discomforting since it provides a guideline rather than a definitive recommendation. A second approach to the problem, the comparison to the better known vertical well, seems in order. We choose reasonable stress values for three tectonic environments.

a) The active thrust fault conditions*: $\sigma_H > \sigma_h > \sigma_z$

b) The post-thrusting for foreland condition: $\sigma_H > \sigma_z \cong \sigma_h$

c) The active extensional (growth faulting) conditions: $\sigma_z > \sigma_H > \sigma_h$**

* not generally an oil exploration realm,

** the strong alignment of the faults indicates that: $\sigma_H > \sigma_h$ (JONES & WALLACE, 1974, p. 512, fig. 1; WEBER & DAUKORNU, 1975, p. 214, Fig. 4).
For the condition: $\sigma_H \sim \sigma_h$ fault strike should be very variable.

We choose the following numerical values and obtain the corresponding maximum tangential stress at the borehole wall:

a) $\sigma_H = 3\sigma_z$; $\sigma_h = 1.5\sigma_z$ $\qquad \sigma_{\theta max} = 7.5\sigma_z$

b) $\sigma_H = 1.5\sigma_z$; $\sigma_h = 1.0\sigma_z$ $\qquad \sigma_{\theta max} = 3.5\sigma_z$

c) $\sigma_H = 0.8\sigma_z$; $\sigma_h = 0.4\sigma_z$ $\qquad \sigma_{\theta max} = 2.0\sigma_z$

It is obvious that the horizontal well is in no more danger of spalling than the vertical well. To state it conservatively: all the experience gained about the instability of vertical wells is applicable to the horizontal well. Vertical wells are generally mechanically stable in reservoir rocks (WOODLAND, pers. com.). This may help to make engineers more comfortable with the horizontal well.

In a field where open fractures affect the fluid flow pressure maintenance is of utmost importance. All stresses mentioned in this paper are effective stresses and thus subject to change as the pore pressure varies. In particular a decrease in pore pressure — as occurs during reservoir depletion — will increase all effective stresses. As the pore pressure drops below a critical value (p_C) the fractures around the well will close and «the tap will be turned off» (Figure 10). Pressure maintenance is thus an essential part of the optimum exploitation of a fractured reservoir.

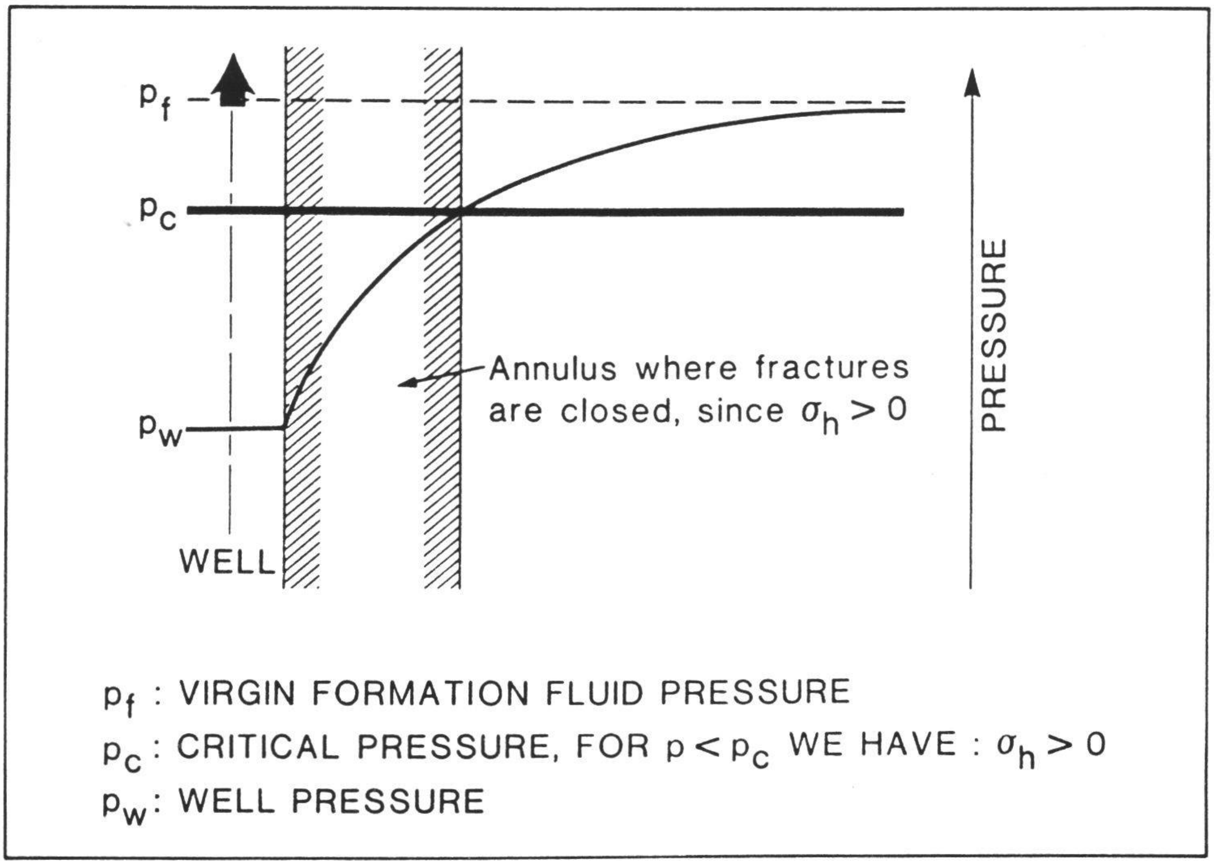

Fig. 10 A producing well may be «shut off» due to closing of the fractures in the immediate vicinity of the borehole. This happens when the well pressure (pw) drops below the critical fluid pressure (pc).

In summary nothing prevents us from using the open-hole parallel completion technique: the drilling technology exists, the costs are already reasonable and falling, mechanical stability can be expected in most cases, and, most important, the parallel completion (horizontal well) offers numerous advantages some of which are listed in Table 3.

SOME ADVANTAGES OF THE PARALLEL COMPLETION TECHNIQUE
*1. Intersects open fractures, important for the one-set fractured reservoir where artificial fracing will only produce another parallel fracture (recognizes reservoir anisotropy)
2. Better chance of intersecting high permeability pods of intermediate size (recognizes reservoir heterogeneity) improves near-well permeability and reduces «natural formation damage»
3. Reduces pressure draw-down and associated problems
4. Reduces problems of coning
5. Reduces sand production in formations that contain moveable fines
*6. If properly oriented permits a controlled multi-frac producing an artificial fracture zone in an otherwise unfractured reservoir
7. Can be used in situations where stress barriers in the seals above and/or below the reservoir are insufficient to contain an artificial, vertical fracture
8. The horizontal well will provide information about the lateral heterogeneity of the reservoir. Such knowledge cannot be obtained from the vertical well or outcrop studies. The former provides the vertical stacking of lithohydraulic units and the latter are non-specific, establishing only general principles.

* sensitive to azimuthal orientation

Table 3

In the previous paper we were led to advocate the deviated well primarily because artifical fracturing will not be effective in a one-set fracture reservoir. In the presence of natural, open fractures the virgin stress conditions will be such that the artificial fracture will open parallel to the existing fracture set and there will be no hook-up to the natural plumbing system of the rock (BLANTON, 1982). The concept is shown in Figure 11. Table 3 (which no doubt is incomplete) shows that we have come a long way and that the deviated well offers many advantages not necessarily related to existing natural fractures.

7 More on the «Beaver River Effect»

The Beaver River gas field of northern British Columbia, Canada, was briefly discussed in the previous paper. We felt that a more thorough analysis was called for and present the results in this section. The facts about the Beaver River field are lifted from the excellent paper by DAVIDSON & SNOWDON (1978). The vital statistics of the field are given in Table 4 and the production history is summarized in Table 5. The Beaver River field was classified as a fractured reservoir in the conventional sense. Initial reserve cal-

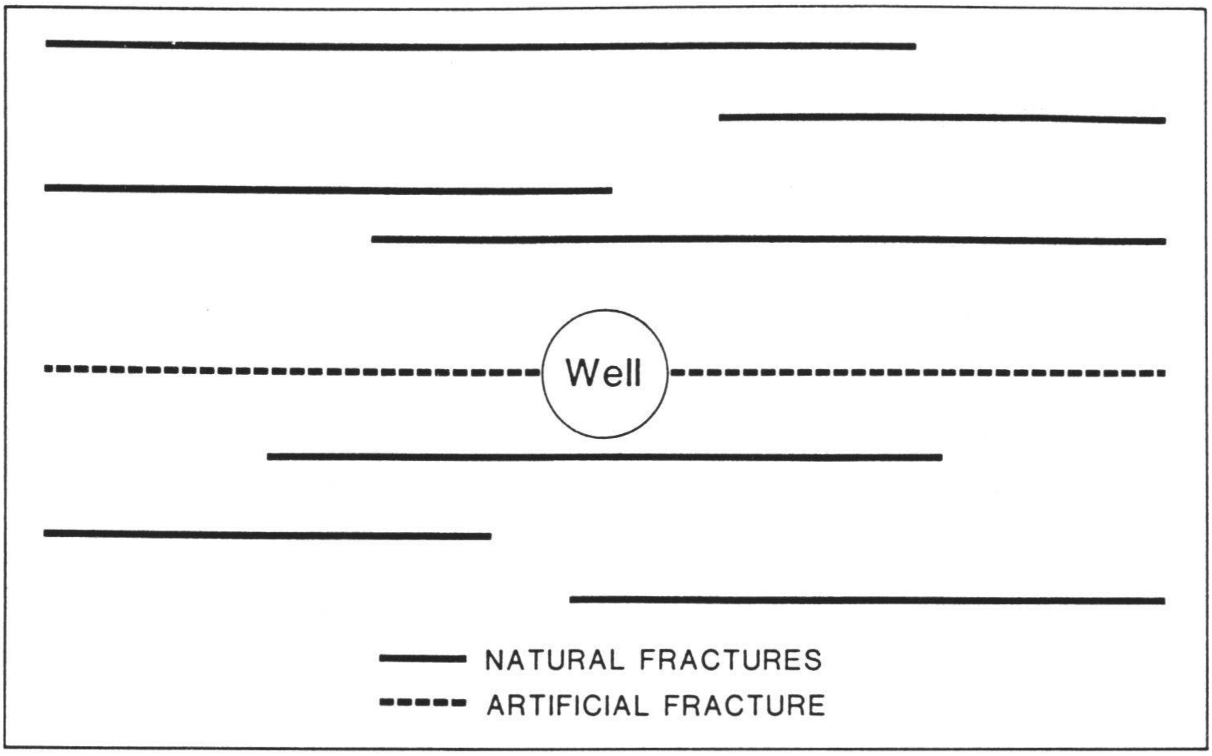

Fig. 11 In a fractured reservoir with a single set of open fractures artificial fracturing will not connect the well to the «plumbing system» of the reservoir.

culations were based on 0% water saturation for the fracture system and 25% water saturation for the matrix pore system for an overall average of 20%. The field was originally a prolific producer but output declined rapidly and after seven years the field had to be shut down having produced only 12% of the initially estimated recoverable reserves.

The field presents the clear lesson that fracture permeability may not always be a blessing. The key to an understanding as to what happened at Beaver River is found in Figure 2 of DAVIDSON & SNOWDON (1978, p. 1673). This map shows the structure contours on the top of the reservoir. We find a steeply, double plunging anticline, in fact the structure is more an elongate dome trending NNE. Two sets of normal faults are shown striking NNE an WNW. This strongly suggests 2-D stress relief, permitting two sets of open, vertical joints. Under such conditions the fracture/matrix permeability contrast will be extreme (see section 2). The field is also under a very strong water drive, the aquifer outcropping some 140 km (85 mi) to the north has a hydraulic gradient of about 0.03. The two factors of a high permeability, two-set open fracture system and a very strong water drive combined to bring about a rapid flushing of the fracture systems with no time allowed for any interaction with the matrix. Once the water formed a continuous phase in the fractures the matrix blocks remained inert, quite analogous to what is known to lead to irreducible oil saturation on the microscopic scale. The message is clear: 2-D fracture systems do not make good reservoirs.

The case for 3-D fracture systems may be different. Under such conditions vertical dilatancy will take place and the fractures may not only provide continuity but also considerable volume (porosity). Such reservoirs may be highly economical. Indications are that the Alborz structure in Central Iran is of this type (GRETENER, 1982 b).

VITAL STATISTICS OF THE BEAVER RIVER RESERVOIR, B.C. CANADA	
LITHOLOGY	DOLOMITE
AGE	MIDDLE DEVONIAN
DEPTH	(12600 Ft) 3850 m
INITIAL PRESSURE	(5836 psi) 40.3 MPa
AVERAGE POROSITY	2.7%
RANGE OF MATRIX PERMEABILITY	<1 - 200 mD
VOLUME	(320×10^9 cft) 8.9×10^9 m^3
MAXIMUM GAS COLUMN	(2950 ft) 1200 m
NET PAY	(900 ft) 270 m

Table 4

PRODUCTION SUMMARY OF THE BEAVER RIVER RESERVOIR, B.C. CANADA		
ESTIMATED RECOVERABLE RESERVES 1971	(1.47×10^{12} cft)	41.6×10^9 m^3
ULTIMATE RECOVERED GAS 1978	(1.78×10^9 cft)	5.0×10^9 m^3
DAILY PRODUCTION, LATE 1971 TO EARLY 1973	(200×10^6 cft)	5.7×10^6 m^3
DAILY PRODUCTION 1973	(60×10^6 cft)	1.7×10^6 m^3
DAILY PRODUCTION 1977	(10×10^6 cft)	0.3×10^6 m^3
SHUT DOWN 1978		--------

Table 5

Another factor that is noteworthy about the Beaver River reservoir is the following. Displacement of the gas/water contact across the normal faults indicates that these faults act as seals despite the extensional environment. A similar observation is reported for the Florence Field in Colorado (WEIMER, 1980). In this case the oil is located in the fractured Pierre shale on the flank of the anticline. Updip movement was prevented and WEIMER (1980, p. 27) had this comment: «The updip seal on the reservoir appears to be impermeable clay gauge zones along faults and fractures between the field and the crest of the Brush Hollow anticline». WEBER ET AL. (1978, p. 2653, Fig. 11) provide an explanation how faults, even in an extensional environment, may develop such sealing qualities. Given the proper circumstances (sand/shales ratio not too high, shales evenly distributed through the section, etc.) the shales will be smeared out along the fault plane and produce a continuous clay gauge lining. In bodies of pure sand such faults (shear fractures) are liable to be fluid conduits due to the dilatancy taking place along such fractures (MEAD, 1925) as shown in the «Huppert Sandbox» (HUBBERT, 1951).

Later examination of plug samples of the Beaver River reservoir revealed that the initial assumption of 25% water saturation for the matrix was in error and water content ranged from 50 to 80%. This indicates that the fractures were formed early, predating reservoir filling and thus played an unfavourable role during gas accumulation. Thus post-migration fracturing is desirable for those reservoirs where the matrix contributes most of the volume (porosity) and fractures merely enhance the permeability.

8 Three Minute Summary

1. Stress relief is necessary for fractures (joints) to be open in the subsurface.
2. It is at this time not sure whether full stress relief (zero normal stress) is necessary for fractures to act a fluid conduits. All one can say is that a zero or low level of normal stress promotes fracture permeability.
3. Stress relief can be of the 1-D, 2-D, or 3-D type.
4. Stress relief can locally occur in any structural province.
5. Stress relief is concentrated in the outer part of bent beams. Thus open fractures tend to further enhance the natural heterogeneity of rocks.
6. 1-D stress relief produces a single set of open fractures. This is expected to be the most common occurence of open fractures.
7. The single set of open fractures acts as a «pipeline with constrictions», since the fluid must migrate through the matrix in order to travel from fracture to fracture. The fracture/matrix permeability contrast is usually less than 100 and often in the range of 5 to 10. Such fractures enhance both reservoir anisotropy and heterogeneity.
8. Multi dimensional stress relief results in open fracture networks. Permeability contrasts may be very high and matrix drainage poor (Beaver River Effect).
9. 3-D stress relief will occur under very high pore pressure (hard geopressures) approaching the value of the lithostatic stress. Under such conditions vertical dilation will take place and the random fracture network will not only provide permeability but also contribute porosity.
10. In the presence of open fractures reservoir pressure maintenance is of great importance else «the tap will be turned off».
11. The term LITHOHYDRAULIC UNIT requires further definition. In particular a differentiation of intra- versus inter-unit variations is needed.
12. Horizontal wells can be assumed to be stable (no spalling) to depth of about 3500 m. Very weak reservoir rocks may fail at depths greater than 2000 m whereas very strong rocks may be stable to 5000 m or more.
13. In view of the extreme heterogeneity of rocks infill drilling should proceed as the parallel, open hole completion.

14. The azimuthal orientation of a horizontal well may be determined from the general structural grain or from the orientation of the breakouts (4-arm dipmeter log).
15. The azimuthal position of the well is usually not very critical since fracture spacing is insensitive to orientation with +-20°. In contrast vertical tolerance is often very limited.
16. Production through perforations may be less ideal than is currently believed. A return to the barefoot completion should be investigated.
17. Infill drilling with the parallel, open-hole completion is at this time the most effective form of better oil/gas recovery.

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