Some mechanisms for the genesis of fractures in sedimentary rocks

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ABSTRACT: Understanding the spatial and temporal distribution of fluid flow in the subsurface is of fundamental importance to the successful management of groundwater and hydrocarbon resources. The analysis is restricted to open mode fracture sets, usually recognized for important contributors to permeability in the case of low porosity reservoirs. We investigated, on a mechanical basis, several field representations likely to occur when jointing and fracture clustering take place. Clustering cannot be explained by effective horizontal tensional conditions resulting in fluid driven fractures, in view of the screening effect between very closely spaced fracture planes, even if we assume sub-critical propagating conditions. Systematic joints form at depth, as a result of tectonic compression in combination with high pore pressure. Unconfined effective conditions arise to produce low rock strength and brittle deformation and load parallel extension fractures are the rule.

1 INTRODUCTION

The importance of fractures and faults in hydrocarbon entrapment, migration and flow has just been recently recognized. The previously common attitude that most basins and reservoirs have no fractures or faults is now impossible : in particular, tight reservoirs discourage any attempt to get a reasonable view of gas or oil recovery by conventional models.

Three common structural types may be considered :

-dilatant fractures (joints, veins, dykes and sills also known as hydraulic natural fractures)

-contraction/compaction structures (compaction bands)

-shear fractures (faults)

Figure 1. Systematic vertical jointing

1.1 *Joints and faults*

Joints are a distinct mode of geologic fracture, distinguished from faults in that the displacement that occurs across the fracture interface is a dilation. Because joints often occur in parallel trending sets of closely-spaced fractures, they can control the mechanical and hydraulic properties of the enclosing rock mass. Consequently, joints affect the productivity of oil and natural gas reservoirs.

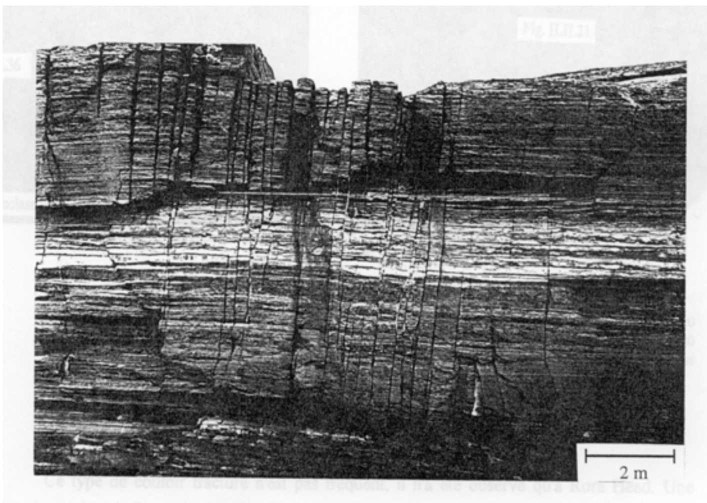


Figure 2. Fracture swarm

1.2 *Objectives of this presentation*

The objective of this presentation is to get a synthetic view of what is possible in the arrangement of joints (opening mode fractures) on a sound mechanical basis, spatially and temporally speaking.

More precisely the matter is about statements assessing the evolution of fractures during genesis of the reservoir. It means a complex loading time history coming with diagenetic processes during lithification, tectonics. A great number of unknown variables may explain the variety of situations ; rock constitutive relationships, structural heterogeneities, abnormal pore pressure, triaxial stress tensor at the time of fracturing.

1.3 *Pore pressure and tectonics*

Historically, it was commonly believed that open fractures could not exist at depth. However, as the role of pore pressure in the reduction of effective stress began to be recognized, open fractures at depth began to be considered not only possible, but entirely likely under certain conditions.

Many attempts have been made in the past to justify the existence of effective tractions orthogonal to joint plane (horizontal tractions for most of the cases). Excessive pore pressure has been generously invoked, joints propagating as natural hydraulic fractures. In the most common version of the assumed mechanism, abnormal formation pore pressure is supposed to exceed the least compressive horizontal principal stress, causing failure within the rock. But many arguments such as fracture morphology are telling against this interpretation.

According to Bessinger et al. (2003) compression driven tensile fracturing mechanisms during jointing has not yet been recognized as important. Evidence for joint–parallel compressive stresses in the vicinity of small or large scale heterogeneities has been demonstrated by field observations and measurements.

Oil industry (Fonta et al. 2005) is indirectly aware of such behaviour : non-tectonic fractures – mainly early diagenetic features – are differentiated from tectonic fractures, with only the latter having a real potential effect on production.

1.4 *Joint size and shape*

Engineering studies have examined joint spacing distributions, but because they typically do not separate genetically distinct joints, their measurements contribute little to the scientific understanding of joint development (Narr & Suppe 1991). The standard engineering technique involves measuring the spacing between joints along a borehole of arbitrary orientation.

Assuming for simplification parallel joint sets, we distinguish between :

-systematic jointing (Fig.1) scaled by layer thickness

-multilayer jointing encouraging to define a "mechanical unit" larger than the stratigraphic unit (Cooke & Underwood 2001)

Aspect ratio, length over spacing, is a useful parameter for capturing typology of fracture.

- -systematic jointing, scaled with stratigraphic or mechanical units has been classically explained using remote tension perpendicular to fracture ;
- -for clustering (Fig. 2) there is no satisfactory answer of this type.

2 EARLY IDEAS

2.1 *Importance of pore pressure*

Joint propagation occurs when appropriate failure criteria are met ; they are often specified in terms of states of stress considered as function of depth of burial, variation of rock properties during consolidation and diagenesis, stress history and pore-fluid pressures. Of particular interest is for Engelder (1985) the "evidence" that joints propagate as *natural hydraulic fractures* under the influence of abnormal pore pressure. According to him, two types of joints may be distinguished : those propagating while burial is in progress and those propagating during erosion and uplift. Abnormal pore pressures are required in the former case whereas thermal-elastic contraction is primarily responsible for the latter case. *Hydraulic* joints are those caused by abnormal pore pressure during burial under restricted pore-water circulation (these joints form at depths in excess of 5km). *Tectonic* joints are distinguished from hydraulic joints in that they form at depth (less than 3km) under the influence of high pore pressure which developed only during tectonic compaction (no overpressure during burial). Active compression of the host rocks is needed in this case to account for abnormal pore pressure. *Unloading* and *release* joints form in response to the removal of overburden during erosion (Nur, 1982).

2.2 *Modelling fracture sets*

Although joint spacing is found to be roughly proportional to layer thickness in many studies, data are not always consistent with each other (Wu & Pollard 1995) and they have lead to contradictory conclusions about the jointing process. One possible explanation is that the data collection methods introduces significant bias. Another possibility is that the 2D linear mechanical relationship between spacing and thickness is too simplistic.

Indeed, the development of a joint set is a complex 3D process with possible changes during the history for physical conditions and loading. Joint fractography and petrophysical properties may help to find the timing of fracturing. These properties allow sometimes to identify depth of burial and variations of pore pressure.

2.3 *Experimental modelling*

Experimental models based on brittle coating techniques share some of the kinematics features such as lateral propagation parallel to bedding. Trends about sensitivity of spacing to parameters are studied by changing the thickness of the brittle coating. Observing joint sets on bedding planes are a necessity when propagation is dominantly parallel to bedding ; spatial distribution of these joints is not visible in layer cross-sections.

As far as geometry of fractures sets is concerned, two kinds of joints sets are distinguished on bedding surfaces (Wu & Pollard 1995): a *poorly-developed* set represents the early stages of development when typical joint lengths are less than typical spacing ; a *well-developed* set represents later stages when lengths are much greater than spacing.

Rives et al. (1992) have studied how the frequency distribution of spacing depends on the stage of development of fracture sets.

2.4 *Modelling geometry of fracture set in a semi-infinite medium: extension cracking*

The first attempts of mechanical analysis are found in Lachenbruch (1961) who connects brittle cracking in the direction normal to the component of maximum tensile stress with many conditions of geologic interest. He points out the interest of Irwin's modification of Griffith's theory and considers useful to describe initiation in terms of "tensile strength" which is the macroscopic average tension under which small flaws start to grow and coalesce whereas macroscopic size cracks are more relevant to an energy criterion. Examples are thermal contraction cracks in cooling basalt, desiccation cracks in mud, tension cracks on the convex sides of flexures. The crack is generally initiated at a surface of great stress (often at or near the ground surface) and is propagated toward the interior of the medium where the tension decreases and ultimately passes in compression.

Depth and spacing give information about the mechanical conditions under which the cracks formed. Scale is partly provided by Irwin's internal length l_0 and partly by an implicit geometric parameter.

$$l_0 = \frac{EG_c}{\sigma_c^2} \qquad (1)$$

2.5 *Single layer configuration: jointing by bending*

Kemeny & Cook (1985) present a similar model to that of Lachenbruch, except that geometry is limited according to a finite layer thickness *h* assumption. Boundary conditions consistent with the process of *tectonic uplift* at some depth below the surface are assumed, with *bending* along *gravity* as loading parameters. Initiation length of cracks is characterised as the actual depth reached at the stable equilibrium point, whereas average spacing is determined by a principle of least amount of energy.

2.6 *Aspect ratios for single layer jointing*

As mentioned before, average spacing *w* between parallel growing cracks and length *a* (Fig. 3) are parameters of great concern.

Reduced toughness κ allows to condense in an appropriate way what is rock relevant and what is connected to geometry (*h* is here the layer thickness as the relevant scaling parameter). We write (Putot et al. 2001):

$$\kappa = \left(\frac{l_0}{h}\right)^{1/2} \qquad (2)$$

κ parameter collects synthetically all information needed to express results in terms of :

w average spacing between fractures
a fracture length (or height)
h layer thickness ; might be considered as the independent leading parameter.

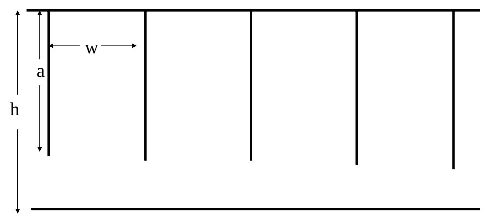


Figure 3. Fracture spacing w and length (height) a in a bed of thickness h

Following equivalencies between geometric mean values have been obtained (Putot et al. 2004):

$$\frac{w}{h} \approx \kappa^3 \qquad \frac{w}{a} \approx \kappa^2 \qquad \frac{a}{h} \approx \kappa \qquad (3)$$

2.7 *Some trends*

Describing variations of *w* and *a* with layer thickness *h* requires statement of hypotheses on our mixed failure criteria:

1st hypothesis : we speculate (usual formulation, Ladeira & Price, 1981) that toughness EG_c is constant with layer thickness *h* but σ_c is decreasing with *h* according to $\sigma_c \approx h^{-1/2}$

For these conditions l_0 is proportional to *h* and κ is constant when *h* is varied. Geometrical characteristics are proportional to thickness of the layer *h* according to :

$$w \approx a \approx h \tag{4}$$

2nd hypothesis : toughness is still constant with *h* but $\sigma_c \approx h^{-1/6}$

For these conditions, l_0 is proportional to $h^{1/3}$ such that κ varies according to $h^{-1/3}$; *w* is constant

$$(w \approx h^0) \text{ and } a \approx h^{2/3} \tag{5}$$

This last hypothesis is in better accordance with observations when dealing with large layer thicknesses (also Ladeira and Price, 1981). Spacing is no longer depending on bed thickness scaling.

The example presented in Figure 4 shows results of the numerical model described in (Putot et al. 2001) for superficial geologic settings and rock types (predominantly bending).

Carpinteri et al. (2005) provide a statistical model to the size effect on grained materials tensile strength and fracture energy very close to our second assumption.

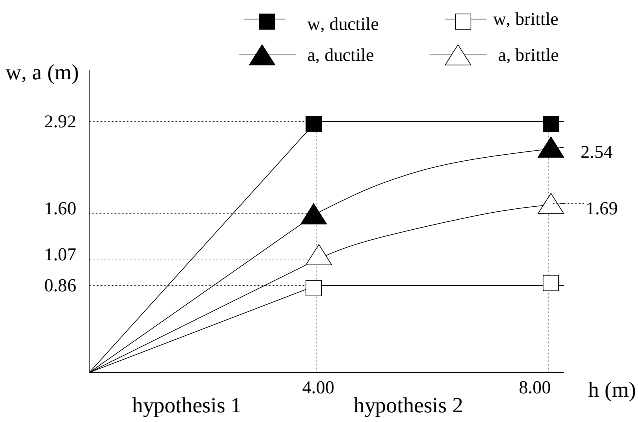


Figure 4. Results of the numerical model, spacing w and fracture length *a* as a function of layer thickness h for conditions of low hydrostatic pressure (predominant bending).
K_{IC} = 1MPa√m σ_c= 3.3 MPa ductile rock
K_{IC} = 1MPa√m σ_c= 5 MPa brittle rock

3 MULTI LAYER JOINTING AND FRACTURE SWARMS

3.1 *Some evidence for multi layer jointing*

Models have attempted to assess the processes and parameters important in determining joint spacing. For most of them, as was pointed out in the last section, the computed joint spacing depends on the thickness of the jointed layer, on a contrast in physical properties between the jointed layer and adjacent beds and on layer-parallel extensional strain. Actual joint spacing distributions seem to differ somewhat from these models: consistent bed-thickness to fracture-spacing relationship can be demonstrated for evenly bedded lithologies, but it deteriorates rapidly as bedding thickness increases.

Narr & Suppe (1991) consider that spacing of joints should be referred to "mechanical layer" thicknesses rather than to individual "bed" thickness, to emphasize the fact that joints are confined to mechanically determined layers, which may nevertheless contain significant bedding planes and sedimentary laminations that are cross-cut by the joints.

Strata are either "brittle", meaning they sustain a well-developed joint system, or else are relatively soft and have poorly-developed joint systems. The "brittle" rocks are harder and more cohesive, the softer are principally mudstone and shale.

All these considerations seem to point out that some kind of interbedding (rock properties, shale thickness) is more prone to arrest fractures, the reason why it is suggested to investigate the bed /interbed coupling.

3.2 *Vertical initiation and propagation ; horizontal propagation*

The most fundamental features of a joint surface include an initiation point and the associated hackle, which have been termed a *plumose structure*. Typically, initiation points are almost always located at bedding interfaces. *Hackle*, the slightly curved topographic feature formed parallel to the local propagation direction and perpendicular to joint front, is remarkably well developed on fine grained rocks. Growth kinematics of successive joint fronts can be analyzed in order to elucidate history of jointing. Joints initiated at the bottom of the layer propagate vertically upward. Reaching the upper interface with shale, further vertical propagation seem inhibited. Propagation then proceed laterally in both directions until conditions for joint propagation are no longer met (Fig. 5).

Composite joint features in several siltstone contiguous layers have been analyzed : each individual layer has its own plumose structure, indicating apparent independent sequential initiation and propagation of each layer.

3.3 *Fracture swarms (clusters)*

Full development of joints, for which lengths are much greater than spacing, have been studied for fractures confined to *one single bed*. Brittle coating techniques seem then appropriate for an analogue experimental model. Nevertheless, we notice that spacing is regular and with order of magnitude close to thickness of the coating.

The geometry of fracture swarms or clusters appear very different : length of fractures is well developed in *two directions*, the order of magnitude being several hundred meters length, not only parallel to bedding but also perpendicular, exhibiting a large degree of "persistency" across layers.

No adequate explanation has been found yet for fracture swarms which are nevertheless of great importance and interest for petroleum geologists, particularly for tight gas reservoirs.

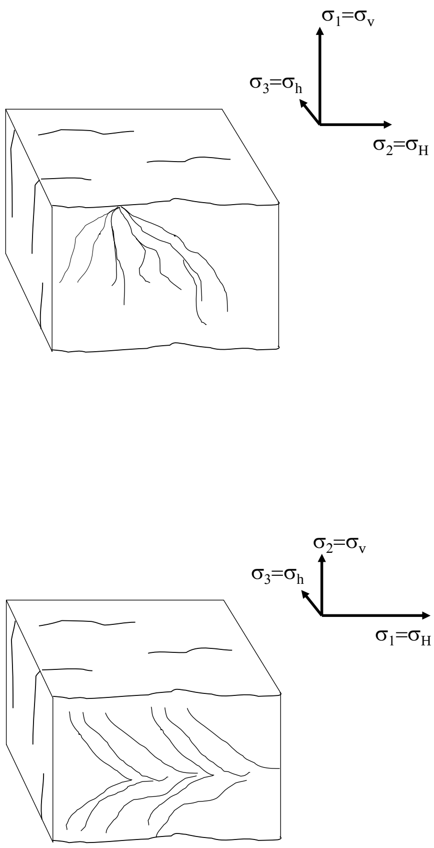


Figure 5. Schematic representation of plumose structure for vertical and horizontal propagation : non tectonic and tectonic case

3.4 *Olson's picture of clustering*

A step towards understanding the process has been numerically achieved by Olson (2004). He considers the dynamics of pattern development for large populations of *layer-confined fractures*. His position is very close to that of brittle coating techniques. He assumes that the initial starter flaws, no matter how short (10 cm in practice), extend across the full thickness of the layer (8m for the presented example), neglecting the initiation and initial vertical propagation. The simulation results demonstrate the apparent important role of the sub-critical crack growth characteristic (expressed by a power-law relationship) in the control of the joint spacing to bed thickness ratio. The idea is that a propagating joint causes the stresses ahead of the tip of a blunted crack to be more tensile, promoting the growth of nearby fractures in a manner similar to the process zone often observed around igneous dykes, where the density of dykes-parallel joints is found to be very high close to the dyke.

A similar analysis is developed by the authors (Picard 2005) when considering the cluster as a large blunted crack (see section 4.4) and discriminating between propagation of the fracture swarm as a whole or involving initiation of a crack as a prerequisite first step (see section 4.4 and Figure 8).

4 FURTHER INVESTIGATION TRACKS

4.1 *The inheritance of quasi-brittle materials formulations*

Quasi-brittle behaviour seems to be the most relevant frame for studying propagation of large size fractures at the reservoir's scale. Failure of brittle materials under triaxial compression has been an important issue for many years.

We proposed an approach which allows to predict crack initiation at V-notches, interfaces with contrasting mechanical properties and various geometrical non singular concentrators such as circular cavities (Picard et al. 2006, Leguillon et al. in press).

The analysis is based on a two-scale asymptotic approach in plane strain elasticity. Far and near representations of the stress and displacement fields are matched in accordance to remote loading and geometry of the microstructure. A mixed criterion involving an energy balance and a maximal stress allows to determine the crack jump at initiation. This length depends on material properties and on the dimension of the local geometry around the stress concentration point (Leguillon 1993).

Interpreting the geologic history from vertical outcrop patterns of fractures requires consideration of tectonics and stratigraphy, which can both produce variations in the fracture pattern.

Modelling fracture mechanisms and possible arrests at interfaces follows a similar approach.

4.2 *A fracture swarm model, considered as representative of a low confinement effective situation.*

A brief presentation of the model developed in Putot et al. (2001) is made in the following. It allows some features of the complex phenomenon of failure in compression in a low confinement situation (Kendall 1978) to be addressed. It is similar to situations discussed by Vardoulakis (1986) considering spalling mechanisms in the vicinity of a stress-free surface. The use of such a model is justified by the very low effective horizontal stress demonstrated to be realis tic for generation of regional fractures (see section 5).

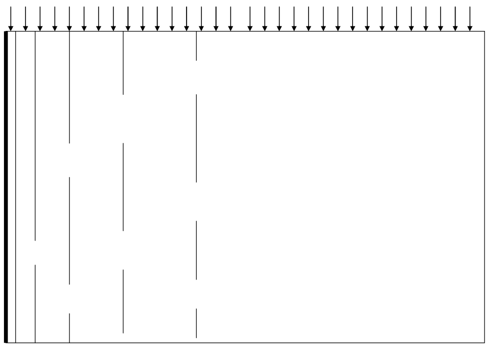


Figure 6. Final state of the fracture swarm

A figurative view of the idealised fracture swarm is presented Figure 6 ; the axis of symmetry is on the left. The important facts are:

When considering fractures close to the assumed free surface (confining parameter equals zero) spacing *w* reaches a well defined limit depending on fracture properties and aspect ratio *a/w* remains unspecified : any ratio is possible and long fractures are statistically the most likely.

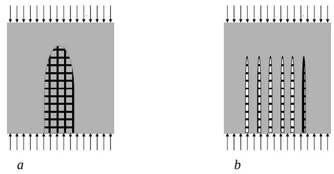
The dual proposition concerns the fracture swarm's margin, where *a/w* ratio is reaching a specified limit whereas spacing *w* remains unspecified (no bedding in this model as a scale parameter).

4.3 *Joint propagation across interbedding*

Three types of fracture behaviour have been investigated : fracture transection through bed contacts, termination at interface and step-over. Conclusions have been inferred, considering strength parameters at the interface coupled with geometrical and loading parameters (Picard et al. 2004a, b). Size effects have also been investigated (Leguillon et al. in press)

4.4 *Modelling a cluster as a process zone*

The formation of closely spaced fractures involves the process of fracture set initiation, propagation and arrest. The only loading likely to lead to a reproduction in exactly the same shape –as a steady state process – seems to be a compressive stress parallel to the fracture planes (Figs 7, 8). Actually, whatever the density of clustering, such a loading is able to make cracks ignore each other. More exactly, some interaction may exist, especially when spacing is reduced, but propagation does not prevent the compression to operate and maintain propagation. Moreover, it is necessary to consider realistic fractures, with a finite thickness, (Picard et al. 2006), in order to take into account the propagation of clusters in the plane of fracturing (Picard 2005).



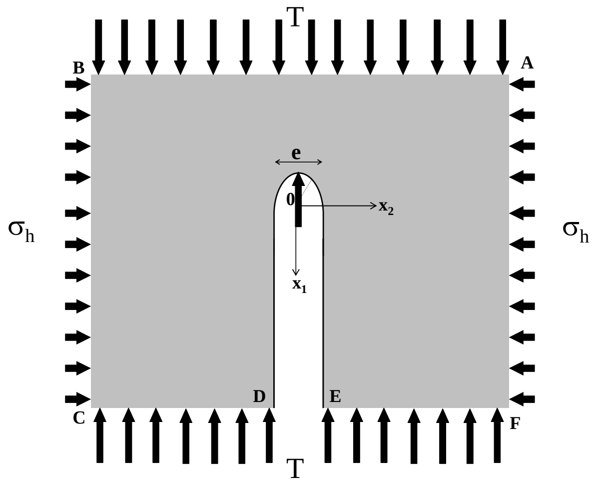


Figure 7. Figurative view of a fracture swarm (cluster)

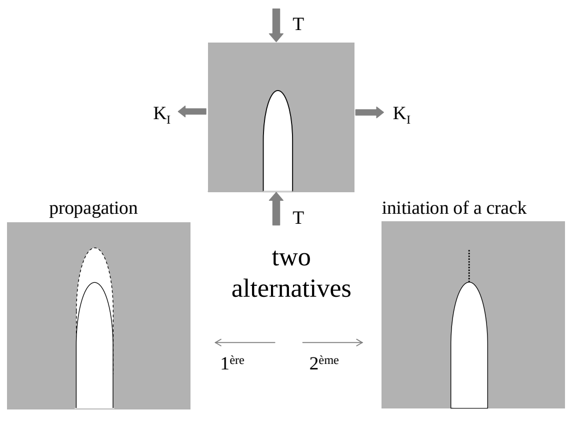


Figure 8. Stationary fracture swarm propagation or initiation of a crack at the notch tip

5 DISCUSSION

Systematic fracture sets have been studied for over a century but divergent opinions and sometimes in-consistent ideas cloud the issue. This section is an attempt to synthesize the most credible mechanisms.

5.1 *Regional fractures, fold related systems and others*

The first idea is the necessity to separate regional fracture systems – the only ones with great economic significance - from fold related systems. Data from both categories have been mixed and some confusion results in interpretations (Lorenz et al. 1991).

It seems realistic that regional fractures sets formed during relatively early deformation, prior to the accumulation of stress that produced flexure. Frequently, horizontal compression apparently fractured the flat-lying strata prior to their incorporation into the fold and thrust belts.

Similarly, cross fracturing systems occur later by stress release during erosion and uplift and are characteristic of younger effects.

5.2 *Load parallel extension fracture*

The load-parallel extension fracture concept is supported by fracture data and morphology ; it has been overshadowed by the concept of natural hydraulic fracturing which is entirely inappropriate in this context. It requires a sustained pressure differential between the fluid within a propagating fracture and the fluid in the pores of the rock, not compatible with usual permeability properties.

The relevant mechanism includes rather the formation, at depth, of regional fractures, as the result of tectonic compression in combination with high pore pressure. Thrusting creates anisotropic horizontal stresses and ultimately fractures in relatively undisturbed strata adjacent to the thrust belt.

5.3 *Triaxial stress state, abnormal pore pressure and tectonics in reservoir*

Fractures propagate preferentially in the horizontal direction if the maximum compressive total stress is horizontal, and vertically if the maximum stress is vertical (Fig. 5). The maximum compressive stress is commonly the vertical overburden stress in undeformed sedimentary adjacent basins. It characterizes the initiation of the tectonic process. Horizontal stress anisotropy requires the horizontal tectonic movement of rocks, the maximum compressive stress being horizontal within thrust belts.

The importance of pore pressure in fracturing is well known, but the mechanical effects of pore pressure are misunderstood and overextended. It is generally implicitly assumed that the total minimum horizontal stress remains constant during increase in pore pressure ; however, it is not the case. As pore pressure is increased, at the same time, an increasing compressive component is added to the total stress. As a consequence, tensile fracturing resulting from vanishing minimum horizontal effective stress is totally excluded, as will be demonstrated in the next section.

5.4 *Proof of unlikely limit case*

Assuming classical effective stress law :

$$\sigma_{\min} = f(\nu, E)\sigma_{\max} \tag{6}$$

where ν and E are Poisson ratio and Young modulus, respectively, f is a function of rock properties which describes how the overburden is transmitted to the horizontal, and Biot relationship between effective stresses and pore pressure, where α is near unity :

$$\sigma' = \sigma - \alpha p \tag{7}$$

the hypothetic limit case :

$$\sigma_{\min} = \sigma_{\max} = 0 \Leftrightarrow p = \frac{\sigma_v}{\alpha} = \frac{\sigma_h}{\alpha} \tag{8}$$

means that the effective horizontal stresses will not reach zero until the pore pressure reaches the overburden value. Note that at failure $\sigma_{max}/\sigma_{min}$ becomes large, although all effective stresses decrease ; the effective stress ratio becoming large is a prerequisite to fracture growth.

Should the limit be attained, this would mean that the rock would be unconfined in effective stress (all compressive stresses equal, with systematic orientation jointing unlikely).

Convergence of pore pressure and overburden stress is nevertheless confirmed in field data, showing that pressure commonly approaches the local overburden stress, but never exceeds it. This proves the unlikely occurrence of zero horizontal effective horizontal stress and tensile fracturing.

5.5 *Brittle behaviour*

Because the strata are almost unconfined (in effective stresses) the rocks yield in load parallel extension fractures at stresses well below those necessary to create folds, faults or shear fractures in the laboratory ; failure could occur with differential stresses of only few MPa under geologic conditions ; the brittleness of rocks at reservoir depths is enhanced by high pore pressure.

5.6 *Low strain rates, presumably sub-critical*

The fractures propagate at quasi-static rates, compatible with geologic phenomena (Atkinson 1984), and probably at rates in accordance with thrust belt tectonic. Some fractographic features such as closely spaced arrest lines are clearly indicative of slow and stable fracture propagation, as opposed to forked terminations indicative of unstability.

5.7 *Subsequent flexure*

Existing regional fractures may be reactivated during subsequent bending of strata, in which case the fracture system may become more permeable. It is not always clear if inherited fractures on structures are or not related to regional stresses that contributed to bending but bending is certainly not the main factor for fracturing.

6 CONCLUSIONS

The genesis of fractures in reservoirs is a complex problem raising questions about loading and scaling conditions in space and time.

Pore pressure exerts a major influence on the effective compressive stresses taken by rocks when fracturing. Nevertheless, balance between pore pressure and compressive stresses is never reached.

Quasi brittle conditions dominate with low effective confinement and relatively low effective failure stresses.

Modeling techniques well suited to structural heterogeneities representation, such as matched asymptotics between near and far fields are useful.

Understanding fracture swarms need further investigation. Several tracks have been proposed. We think that low rate processes at the crack tip combined with extended fracture mechanics are good candidates for a satisfactory analysis, but full validation requires in-situ evidences.

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