A MECHANICAL MODELLING OF THE PRIMARY MIGRATION

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MODÉLISATION MÉCANIQUE DE L'EXPULSION

Dans le but d'étudier le problème de la microfracturation induite par la génération des hydrocarbures dans les roches mères, nous proposons une méthode analytique pour déterminer l'évolution de la pression de l'huile. Cette méthode est basée sur une modélisation mécanique des interactions kérogène-huile-roche à l'échelle microscopique.

Il est montré que la pression de l'huile tend vers une valeur asymptotique quand la réaction de transformation du kérogène en huile s'achève. Les variations des contraintes macroscopiques pendant la formation de l'huile ont des effets faibles. Cependant, ils doivent être considérés pour décrire correctement l'évolution de la pression de l'huile au stade précoce de la génération.

L'augmentation de l'enfouissement provoque une augmentation de la pression de l'huile ainsi qu'une augmentation des contraintes macroscopiques. Cela conditionne l'évolution du champ de contraintes microscopiques. La possibilité de microfracturation dépend de la position du champ de contraintes microscopiques par rapport au critère de rupture. Si la durée de la transformation du kérogène en huile est suffisament courte, de sorte que l'on puisse négliger la variation du champ de contraintes macroscopiques induite par la variation de l'enfouissement, alors, on montre que pour des valeurs usuelles des paramètres mécaniques, la microfracturation est possible. Néanmoins, de façon plus générale, le fait de négliger les variations du champ de contraintes macroscopiques conduit à une surestimation des possibilités de microfracturation induite par l'augmentation de la pression de l'huile.

Á l'échelle macroscopique (de la roche mère), l'équation qui décrit l'évolution de la pression de l'huile est écrite dans le cadre de la théorie poroélastique de Biot. L'évolution de la pression est donnée par la somme d'un terme de diffusion qui provient de la migration de l'huile dans la roche, et de deux termes respectivement associés à l'expansion volumique de la transformation du kérogène en huile et à l'augmentation de la charge due à l'enfouissement.

A MECHANICAL MODELLING OF THE PRIMARY MIGRATION

In order to adress the question of oil-induced microfracturing, we propose under specific assumptions (plane circular kerogen flake surrounded by an homogeneous microfractured porous medium) an analytical method for the determination of the oil pressure increase. It is based on a mechanical modelling of the kerogen-oil-rock interaction at the "microscopic" scale of a kerogen particle.

It is shown that the oil pressure tends towards an asymptotic value when the chemical transformation of kerogen is completed. The effect of the macroscopic stress variation during oil formation process proves to be negligible. However, this effect must be taken into account for describing the evolution of oil pressure at earlier stages of oil formation process.

The increase in burial depth induces an increase of oil pressure as well as a variation of the macroscopic stress which both determine the microscopic stress field. The possibility of microfracturing depends on the position of the microscopic stress state with respect to the fracture criterion. If the duration of the oil formation process is short enough, so that the macroscopic stress change associated with the corresponding (small) burial depth increase can be neglected, it is found that microfracturing is likely for the usual values of rock tensile strength. However, in the general case, neglecting the macroscopic stress change can significantly overestimate the possibility of fracture initiation due to oil-pressure increase.

Considering now the "macroscopic" scale of the source bed, the evolution equation of the oil pressure are derived within the framework of Biot's poroelasticity theory. The oil pressure rate proves to be the sum of a diffusion term which accounts for oil migration within the source bed, and of two source terms respectively associated with the volume expansion tendency of the kerogen → oil transformation and the overburden pressure increase.

MODELIZACIÓN MECÁNICA DE LA EXPULSIÓN

Con objeto de estudiar el problema de la microfracturación inducida por la generación de los hidrocarburos en las rocas madre, se propone un método analítico para determinar la evolución del petróleo. Este método se funda en una modelización mecánica de las interacciones kerogeno-petróleo-roca a escala microscópica.

Se demuestra que la presión del petróleo tiende hacia un valor asintótico cuando finaliza la reacción de transformación del kerogeno en petróleo. Las variaciones de las tensiones macroscópicas durante la formación del petróleo tienen efectos de reducida importancia. No obstante, se deben considerar debidamente para describir correctamente la evolución de la presión del petróleo en la etapa precoz de la generación.

El aumento de la profundización provoca a su vez un aumento de la presión del petróleo, así como un aumento de las tensiones macroscópicas. De ello habrá de depender la evolución del campo de tensiones microscópicas. La posibilidad de microfracturación depende también de la posición del campo de tensiones microscópicas con respecto al criterio de ruptura. Si el lapso de tiempo de la transformación del queroseno en petróleo es suficientemente corto, de tal modo que se pueda considerar insignificante la variación del campo de tensiones macroscópicas inducida por la variación de la profundización, se demuestra entonces que, para los valores de costumbre de los parámetros mecánicos, la microfracturación constituye una posibilidad. No obstante, y de modo más general el hecho de considerar insignificantes las variaciones del campo de tensiones macroscópicas, conlleva a una sobreevaluación de las posibilidades de microfracturación inducida por el aumento de la presión del petróleo.

Operando a escala macroscópica (de la roca madre), la ecuación que describe la evolución de la presión del petróleo figura escrita en el marco de la teoría poroelástica de Biot. La evolución de la presión se obtiene por la suma de un término de difusión que procede de la migración del petróleo en la roca, así como de dos términos respectivamente asociados a la expansión volúmica de la transformación del kerogeno en petróleo y al aumento de la carga derivada de la profundización.

INTRODUCTION

Primary migration refers to the release of petroleum compounds from kerogen and their transport within the source bed. Mechanical modelling of primary migration at the scale of the souce bed (macroscopic scale) is necessary in order to perform global simulations of sedimentary basins. It obviously must take into account the physical mechanism responsible for hydrocarbons migration at the scale of kerogen flakes (microscopic scale), which however remains disputed. The present paper successively deals with the modelling of primary migration at the microscopic and macroscopic scales. For the sake of simplicity, we shall restrict ourselves to the case of a unique hydrocarbon phase (oil).

As far as the microscopic scale is concerned, several authors have suggested that primary migration can occur by means of a set of microfractures induced in the rock by the oil pressure increase (Tissot and Welte, 1984). In order to adress quantitatively this question, we propose a theoretical determination of the oil pressure evolution which is based on a reasoning performed at the scale of the kerogen flake and the surrounding rock material (microscopic scale). The rock material is supposed to be an homogeneous microfractured porous medium. Simultaneously, we compute the stresses induced in the rock at this scale which can be compared to its strength criterion. This approach permits us to discuss the possibility of oil-induced fracture initiation at any stage of the oil generation and is illustrated numerically. In the second part of this paper, we give the basic features of a general theory for primary migration at the scale of the source bed (macroscopic scale). It is developed within the framework of Biot's poroelasticity and is substantiated by the results of microscopic modelling.

1 THE MECHANICAL APPROACH AT THE MICROSCOPIC SCALE

The oil formation process takes place in a source bed subjected to an increase of burial depth. As a matter of fact, the latter is associated with an increase of temperature which activates the chemical transformation of kerogen into oil. In addition, a part of the produced oil can migrate out of the source bed. The oil pressure thus appears as a function of the extents of the oil formation and oil migration processes. Besides, it is reasonable to expect that the increase in overburden pressure and lateral pressure which occurs during burial will also affect the value of the oil pressure. Taking into account both transformation of kerogen and oil migration as well as the variation of the macroscopic stresses, the aim of this section is to determine the oil pressure evolution as a function of the burial depth in order to discuss whether microfracturing in the rock material which constitute the source bed can be induced by the oil pressure increase.

1.1 Schematization of geometry and loading

The proposed approach consists in a mechanical modelling of the kerogen-oil-rock interaction at the microscopic scale. It relies upon a periodic two dimensional schematization of the geometry of the source bed. The cross section of each elementary cell $d\Omega$ is schematized as a square in which the kerogen initially occupies a circular cavity.

The initial volume fraction of the kerogen is denoted by η, the beginning of the oil formation process corresponding to $t = t_o$ (Fig. 1a). At time $t > t_o$, a part of the kerogen has been transformed into oil which now surrounds the remaining part of the kerogen (Fig. 1b). The extent of the oil formation process is defined by the variation of kerogen mass which is denoted by $m_K d\Omega$, m_K thus being equal to 0 at $t = t_o$ and negative for $t > t_o$. We also denote by $m_H d\Omega$ the variation of oil mass in $d\Omega$. Accordingly, the particular case of "undrained" oil formation process would correspond to the condition $m_H = -m_K$. If there is a porous network constituted by microfractures crossing the rock material which surrounds the oil-kerogen cavity, oil is able to migrate outside of $d\Omega$. We observe that $-(m_H + m_K)d\Omega$ represents the oil mass which has actually migrated outside of $d\Omega$ since the beginning of the oil formation process ($t = t_o$). Thus, m_H and m_K are independent parameters by which the extents of both oil formation and oil migration processes can be measured. The elementary cell is subjected to a macroscopic stress state defined by the macroscopic horizontal and vertical stresses S_h and S_v. The vertical stress corresponds to the weight of the overlying material (overburden pressure):

$$S_v(t) = \int_{Z(t)}^{H(t)} \rho(z,t) g dz \tag{1}$$

where $H(t)$ is the current height of the sedimentary basin, $Z(t)$ is the current location of the considered cell at the macroscopic scale, $\rho(z,t)$ being the material unit weight at the same scale. The ratio $k = S_h/S_v$ takes various values notably depending on tectonic activity (Breckels and van Eekelen, 1982).

In order to relate the macroscopic stresses S_h and S_v defined at the scale of the source bed to the microscopic stress field inside of $d\Omega$, it is assumed that a uniform pressure equal to S_v (resp. S_h) is applied to the upper and lower (resp. lateral) boundaries of $d\Omega$. The macroscopic stresses S_h and S_v thus define the mechanical loading to which the elementary cell is subjected.

Besides, observing that the volume fraction of kerogen is of the order of a few percents, it will be possible to replace these stress conditions on the external boundary of the cell $d\Omega$ by two given principal stresses at infinity.

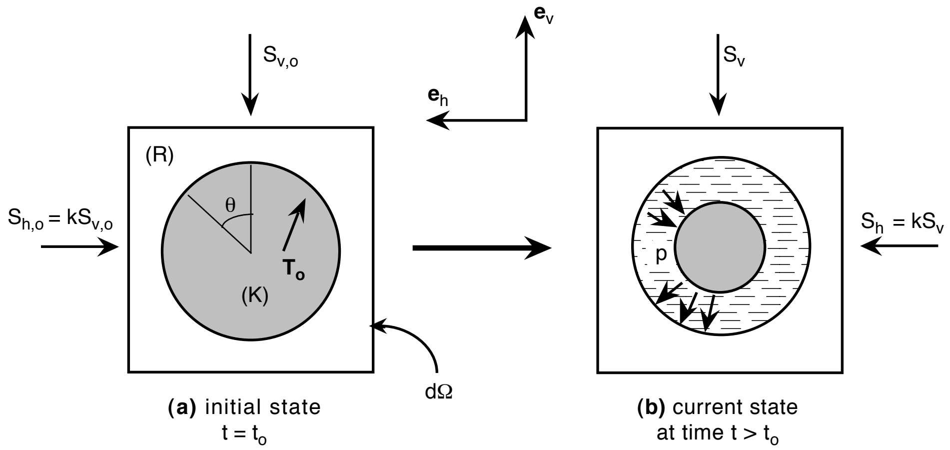

Figure 1

Schematization of geometry and loading.

As far as the initial mechanical state is concerned, we assume that the microscopic horizontal and vertical stresses are uniform in $d\Omega$:

$$\sigma_{v,o} = S_{v,o} \; ; \; \sigma_{h,o} = S_{h,o} \tag{2}$$

where $S_{v,o}$ and $S_{h,o}$ characterize the macroscopic stress state at the beginning of oil formation. Accordingly, at the interface with the kerogen, the rock material is initially subjected to a non uniform distribution $\boldsymbol{T}_o$ of surface forces:

$$\boldsymbol{T}_o = S_{v,o} \cos\theta \boldsymbol{e}_v + S_{h,o} \sin\theta \boldsymbol{e}_h \tag{3}$$

where θ is the angle defined at Figure 1a. After the beginning of oil formation process ($t > t_o$), an oil film surrounds the kerogen, so that a uniform distribution of surface forces equal to the oil pressure p now acts on the rock material at the oil/rock interface, as well as on the kerogen at the oil/kerogen interface (Fig. 1b).

We observe that the stresses in the kerogen are uniform both for $t < t_o$ where they are given by (2), and for $t > t_o$ where $\sigma_v = \sigma_h = p$. This change in the stress state is associated with a change in density. Denoting the current (resp. initial) mass density of the kerogen by ρ_K (resp. $\rho_{K,o}$) and modelling the kerogen as an elastic material, a straightforward analysis shows that:

$$\frac{\rho_{K,o}}{\rho_K} - 1 = -\frac{p - S_o}{K_K} \text{ with } K_K = \frac{G_K}{(1 - 2\nu_K)} \tag{4}$$

where $S_o = (S_{v,o} + S_{h,o})/2$, G_K and ν_K are the shear modulus and the Poisson coefficient respectively. The variation of the oil mass density ρ_H due to the increase in oil pressure will be described by:

$$\frac{\rho_{H,o}}{\rho_H} - 1 = -\frac{p - p_o}{K_H} \tag{5}$$

where K_H is the oil compression modulus and p_o is the value of the oil pressure at the beginning of the oil formation process. It should be noticed that p_o is an unknown variable of the problem which will be determined in the next section.

1.2 Theoretical determination of the oil pressure p

We now present an analytical determination of the oil pressure p as a function of m_H, m_K, S_H and S_V. We can first express the variation ΔV of the oil-kerogen cavity volume V as a function of m_H, m_K, and of the densities of oil and kerogen. It is readily seen that:

$$\frac{\Delta V}{V} = \frac{1}{\eta}\left(\frac{m_H}{\rho_H} + \frac{M_{K,o} + m_K}{\rho_K} - \eta\right) \tag{6}$$

where $M_{K,o} d\Omega$ is the initial kerogen mass contained in the elementary cell. Taking (4) and (5) into account in (6), one obtains:

$$\frac{\Delta V}{V} = \frac{1}{\eta}\left(\overline{m}_H\left(1 - \frac{p - p_o}{K_H}\right) + \overline{m}_K\left(1 - \frac{p - S_o}{K_K}\right) - \eta\frac{p - S_o}{K_K}\right) \tag{7}$$

where $\overline{m}_\alpha = m_\alpha / \rho_{\alpha,o}$ ($\alpha = H$ or K).

The second way to determine the volume variation ΔV is to analyze the displacement field $\boldsymbol{U}$ defined on the rock domain in $d\Omega$ with respect to the initial configuration of the rock ($t = t_o$).

More precisely, ΔV can be derived as the flux of $\boldsymbol{U}$ through the oil/rock interface I, i.e. $\Delta V = \int_I \boldsymbol{U} \cdot \boldsymbol{e}_r dS$, where $\boldsymbol{e}_r$ is the radial unit normal to I.

We model the rock as an elastic material (shear modulus G_R, Poisson coefficient ν_R). The superposition principle then shows that $\boldsymbol{U}$ is the sum of the displacement fields respectively associated with:

– the variation $p\boldsymbol{e}_r - \boldsymbol{T}_o$ of the surface forces acting on the rock at I;
– the variations ΔS_v and ΔS_h of the macroscopic stresses. Solving the mechanical problem yields the following expression of $\Delta V/V$:

$$\frac{\Delta V}{V} = \frac{1}{G_R}\left(p - S_o - (1 - \nu_R)(\Delta S_v + \Delta S_h)\right) \tag{8}$$

in which appears each of the two different components of the loading to which the rock is subjected.

Immediately after the beginning of oil formation, we have $\overline{m}_H = \overline{m}_K = 0$ as well as $\Delta S_v = \Delta S_h = 0$. (7) and (8) respectively yield:

$$\left(\frac{\Delta V}{V}\right)_o = -\frac{p_o - S_o}{K_K} = +\frac{p_o - S_o}{G_R} \tag{9}$$

This establishes that the oil pressure p_o is equal to the initial mean stress S_o:

$$p_o = \frac{1}{2}\left(S_{h,o} + S_{v,o}\right) \tag{10}$$

Eliminating the relative volume variation $\Delta V/V$ between (7) and (8) and using (10), one finally obtains:

$$p - p_o = \frac{(1-\nu_R)(\Delta S_v + \Delta S_h) + \frac{G_R}{\eta}(\overline{m}_K + \overline{m}_H)}{1 + \frac{G_R}{\eta}\left(\overline{m}_K/K_K + \overline{m}_H/K_H + \eta/K_K\right)} \tag{11}$$

With respect to other approaches in the literature (see for instance Ozkaya, 1987), the above expression of the oil pressure allows to quantify the effect of the variation of the macroscopic stress state which can result from an increase in burial depth or from a tectonic activity. It also takes into account the extents of the oil formation and migration processes measured by the oil and kerogen mass changes $\overline{m}_H$ and $\overline{m}_K$.

1.3 Numerical estimates of the oil pressure p

It seems reasonable to assume that the oil formation is an undrained process until a microfracture network has been created in the rock material surrounding the oil/kerogen cavity. We shall therefore restrict in this section to the particular case where the mass changes m_K and m_H are opposite, so that $\overline{m}_H = -\overline{m}_K\, \rho_{K,o}/\rho_{H,o}$.

Let us denote by α the fraction of the kerogen mass which is convertible into oil, and consider the stage where the transformation has been completed, at which we have $\overline{m}_K = -\alpha\eta$. Taking into account the fact that oil is much more compressible than kerogen or than the rock material, i.e. $K_H << K_K$ or G_R, we observe that the expression (11) of the oil pressure increase can be simplified under the form:

$$\begin{aligned} p - p_o \cong\ & K_H\left(1 - \frac{\rho_{H,o}}{\rho_{K,o}}\right) \\ & + (1-\nu_R)\frac{\rho_{H,o}}{\rho_{K,o}}\frac{K_v}{\alpha G_R}\left(\Delta S_v + \Delta S_h\right) \end{aligned} \tag{12}$$

The above equation shows that the oil pressure increase is the result of two distinct contributions. The first term corresponds to the tendency to volume expansion of the kerogen → oil transformation. More precisely, Ungerer *et al.* (1983) and Goff (1983) have obtained values of the mass density ratio $\rho_{K,o}/\rho_{H,o}$ between 1.1 and 1.2, which would correspond to a volume expansion if the kerogen → oil transformation would happen under constant pressure. The second term in (12) corresponds to the overburden pressure increase. However, this effect appears to be considerably reduced by the factor K_H/G which is smaller than 10^{-2}. In practice, this means that the oil pressure increase reaches an asymptotic value which is independent of the variation of the macroscopic stress state and is given by:

$$\Delta p^{\infty} \cong K_H\left(1 - \frac{\rho_{H,o}}{\rho_{K,o}}\right) \tag{13}$$

Hence, focusing the attention on the effect of volume expansion tendency, we obtain $\Delta p^{\infty} \approx 16$ MPa for $K_H = 100$ Mpa and $\rho_{K,o}/\rho_{H,o} \approx 1.2$. The theoretical approach described in section 1.2 not only provides the asymptotic value of the oil pressure. Combined with certain simplifying assumptions concerning the variation of the macroscopic stress state and the oil formation process, it allows to get an insight into the whole evolution of the oil pressure. Denoting by V the sedimentation rate, the burial depth $D(t) = H(t) - Z(t)$ of the source bed will be estimated as $D(t) \approx Vt$, which means that compaction is neglected as far as the determination of the overburden pressure is concerned. Replacing in (1) the local value $\rho(z,t)$ of the rock density by an average density denoted by $<\rho>$, we then obtain:

$$\Delta S_v(t) = \ <\rho> gD(t) \ \approx\ <\rho> gVt \tag{14}$$

For the sake of simplicity, it is assumed that the stress ratio $k = S_h/S_v$ remains constant. In order to model the oil formation process, we adopt a single first order kinetic for the transformation of kerogen, so that the remaining mass fraction of kerogen, i.e. $x = 1 + \frac{m_K}{M_{K,o}}$, satisfies:

$$\frac{dx}{dt} = -Cx \text{ with } C = A\ \exp\left(-\frac{E}{R\tau}\right) \tag{15}$$

The coefficient C in (15) proves to be an increasing function of the absolute temperature τ through the classical Arrhenius formula in which A is a constant and E is the activation energy (Tissot and Welte, 1984). With increasing burial depth, the temperature τ increases according to the local geothermal gradient α. The numerical resolution of (15) reveals the existence of a threshold depth $D_o = Vt_o$ below which $x = 1$ ($m_K = 0$) and above which the oil formation begins ($x < 1$). The results presented at Figure 3a have been obtained for a linear profile $\tau(t) = \tau^* + \alpha D(t)$ of temperature with respect to depth, and for $\tau^* = 0°C$, $\alpha = 0.05°C\ m^{-1}$, $A = e^{64}\ My^{-1}$, $E = 200 kJ{\cdot}mol^{-1}$ and $V = 10\ m \cdot My^{-1}$.

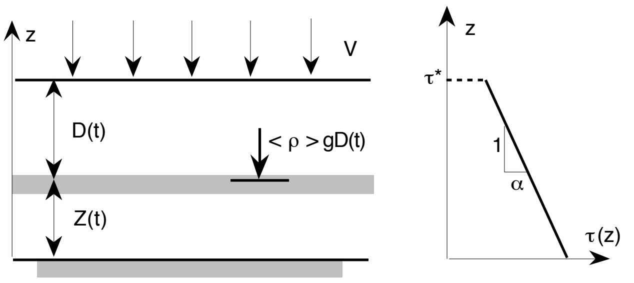

Figure 2

Temperature and macroscopic stress changes with increasing burial depth.

The oil pressure evolution can be predicted by (11) in incorporating in this formula the estimates of ΔS_v and m_K respectively provided by (14) and (15). Figure 3b represents the predicted oil pressure as a function of the burial depth. The solid curve takes into account both the effecs of oil formation and of overburden pressure increase, whereas this second effect is neglected in the dashed curve. As stated before (see (13)), overburden pressure increase becomes negligible at the end of the oil formation process. However, the discrepancy between the two curves shows that this effect *should be taken into account at the early stages*.

1.4 The question of fracture initiation

In order to discuss if the oil formation process and the macroscopic stress changes can induce microfracturing in the rock material surrounding the oil/kerogen cavity, we have to determine the microscopic stress field inside of the elementary cell $d\Omega$ and to compare it to a criterion for fracture initiation at the microscopic scale of the general form $f(\underline{\underline{\sigma}}) = 0$. Within the framework of this two-dimensional analysis and as we assume that the rock is an homogeneous microfractured porous medium, we propose to use the classical plane Griffith criterion (Jaeger and Cook, 1976), which writes:

$$f(\underline{\underline{\sigma}}) = (\sigma_1 - \sigma_3)^2 - 8T(\sigma_1 + \sigma_3) \text{ if } \sigma_1 + 3\sigma_3 \geq 0 \quad (16a)$$

$$f(\underline{\underline{\sigma}}) = -(\sigma_3 + T) \text{ if } \sigma_1 + 3\sigma_3 < 0 \quad (16b)$$

where σ_1 and σ_3 ($\sigma_1 > \sigma_3$) denote the principal stresses, and T is the rock tensile strength *at the microscopic scale*. This means that the size of the microfractures is small with respect to the size of the kerogen flake.

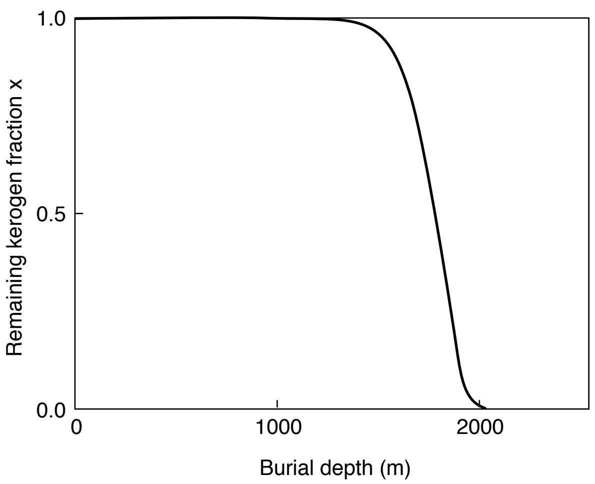

Figure 3a

Evolution of the kerogen fraction as a function of burial depth.

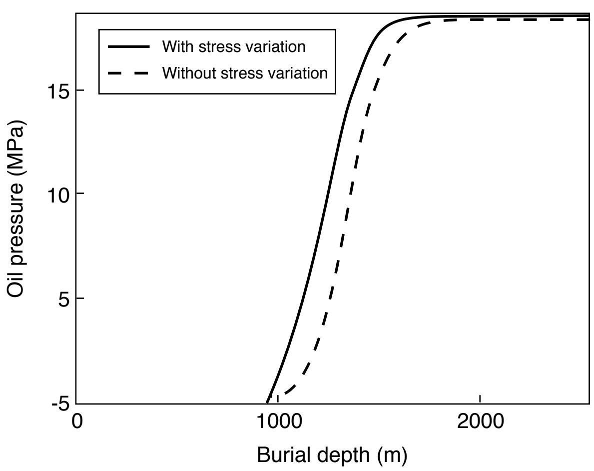

Figure 3b

Evolution of oil pressure as a function of burial depth.

The behaviour is elastic if $f(\underline{\underline{\sigma}}) < 0$ and fracturing is initiated if $f(\underline{\underline{\sigma}}) = 0$.

In the domain defined by $\sigma_1 > 0$ and $\sigma_1 > \sigma_3$, the boundary of the criterion is constituted by a horizontal segment and a parabola. For $\sigma_1 < 3T$, fracturing occurs under tensional conditions ($\sigma_3 = -T$) when the point which represents the stress state reaches the horizontal segment. However, according to Griffith criterion, it can also be initiated under smaller tensional stresses ($\sigma_3 > -T$) or even compressive stresses when the stress point reaches parabola (Fig. 4). For instance, in the uniaxial compression test, fracturing will occur for $\sigma_1 = 8T$ and $\sigma_3 = 0$.

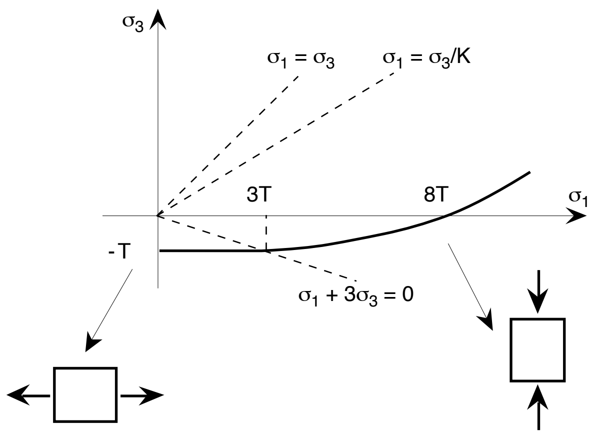

Figure 4

(Plane) Griffith criterion.

According to the superposition principle of the theory of linear elasticity, the current microscopic stress field in the rock domain of the elementary cell proves to be the sum of the stress fields associated with two classical problems (Jaeger and Cook, 1976):

– given cavity pressure in an infinite domain with no stress at infinity;
– circular hole in an infinite domain with two given principal stresses at infinity (Fig. 5). In particular, the radial and orthoradial stresses at the oil/rock interface I are:

$$\sigma_r = p$$
$$\sigma_\theta = -p + \left(S_h + S_v - 2(S_v - S_h)\cos(2\theta)\right) \qquad (17)$$

It can be shown that the most favourable condition for fracture initiation which corresponds to the highest value of the criterion $f(\underline{\underline{\sigma}})$ is realized at the top ($\theta = 0$) and the bottom ($\theta = \pi$) of the oil/rock interface I (Fig. 6). Depending on the location of the point where the criterion boundary is reached in the space of principal stresses (σ_1, σ_3), the condition for fracture initiation writes:

$$T \le T^* = \frac{\left(2\left(\Delta p + S_{v,o}(1-k)\right) - (3k-1)\Delta S_v\right)^2}{8(3k-1)(S_{v,o} + \Delta S_v)} \qquad (18a)$$

(criterion reached on the parabola)

$$T \le T^{*\prime} = \Delta p + \frac{(3-5k)}{2} S_{v,o} + (1-3k)\Delta S_v \qquad (18b)$$

(criterion reached on the line $\sigma_3 = -T$)

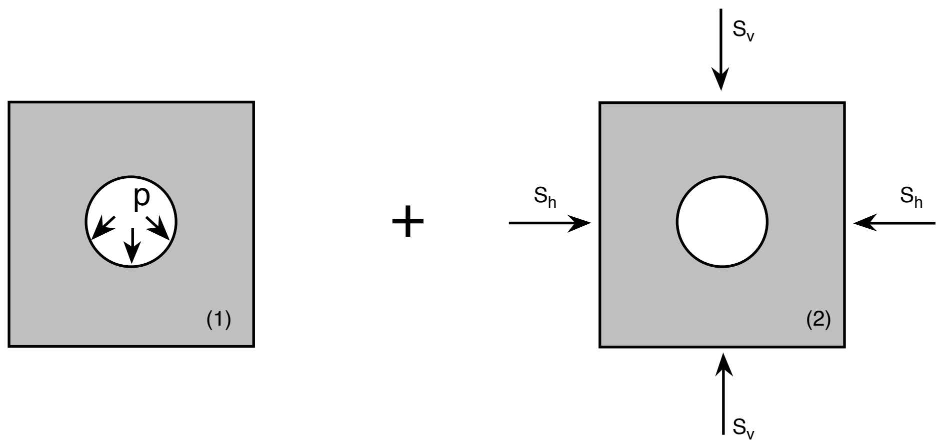

Figure 5

Decomposition of the loading in 2 elementary problems.

In other words, for given values of the stress ratio k, of the initial overburden pressure $S_{v,o}$ at the beginning of the oil formation process, of the oil pressure and overburden pressure increases Δp and ΔS_v, fracturing will be initiated at the top of the oil/rock interface if the rock tensile strength is smaller than the threshold strengths T^* and $T^{*\prime}$ defined by (18a) and (18b). For usual values of these parameters, it can be shown numerically that $T^{*\prime} \leq T^*$, which means that condition (18a) is less restrictive than condition (18b). We shall therefore adopt the expression of the threshold strength T^* given in (18a).

If the variation ΔS_v of the overburden pressure due to burial occuring during the oil formation process is neglected, it is found that the corresponding condition for fracture initiation can be easily satisfied for` the commonly encountered values of Δp, $S_{v,o}$, k and T. For instance, with the previously determined value of the asymptotic oil pressure increase Δp = 16 MPa, and k = 0.75, one obtains T^* = 6.76 MPa for S_v = 40 MPa and T^* = 8.82 MPa for S_v = 20 MPa, which is of the order of typical value of the tensile strength. However, it is readily seen from (18a) that oil pressure increase Δp and overburden pressure increase ΔS_v, which are both consequences of an increasing burial depth have opposite effects on the variation of the threshold strength.

More precisely, the threshold strength T^* is an increasing (resp. decreasing) function of Δp (resp. ΔS_v). This means that, contrarily to the oil pressure increase, the increase in overburden pressure tends to prevent the initiation of fractures. Thus, a detailed analysis is necessary to quantify the combined influences of oil pressure and overburden pressure increases.

The stress path associated with the microscopic stress state at the top of the oil/rock interface which is the most favourable location for fracture initiation (Fig. 6) is represented in the stress plane (σ_1, σ_3) at Figure 7. The stress point moves on this path as the burial depth increases.

Segment AB describes the evolution of the stresses for $t < t_o$, i.e. before the beginning of the oil formation process which corresponds to point B. In accordance with (2), the major principal stress σ_1 is equal to the overburden pressure S_v and the slope of AB is equal to the stress ratio k.

For the values of k and of S_v encountered in practice, this line never intersects the boundary of the criterion.

Once the oil formation has begun, an oil film separates the kerogen from the surrounding rock. This implies a significant stress change at $t = t_o$.

As a matter of fact, for $t \geq t_o$, σ_1 is equal to the oil pressure $p = p_o + \Delta p$. Thus, at $t = t_o$, σ_1 decreases from $S_{v,o}$ to the initial oil pressure p_o which has been found to be equal to $S_{v,o}(1 + k)/2$ (see (10)). Segment BC corresponds to this discontinuity of the microscopic stress state which is associated with a movement of the stress point towards the boundary of the criterion.

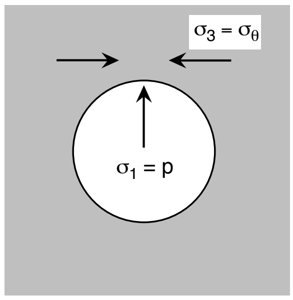

Figure 6

Most favourable location for frature initiation.

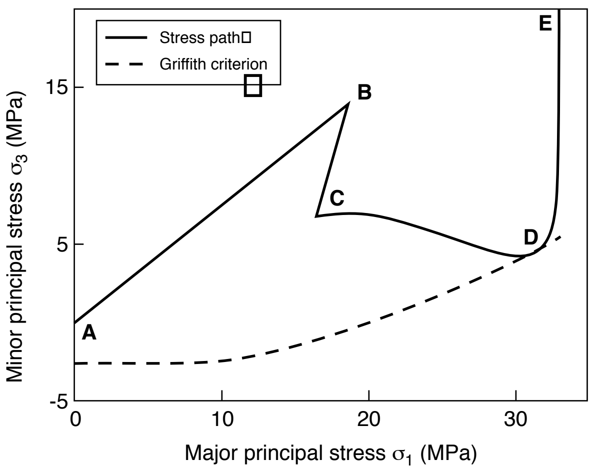

Figure 7

Stress path asociated with microscopic stress state at the top of oil/rock interface.

Beyond point C, the oil formation process can be divided into two parts. During the first stage (curve CD), the increase of oil pressure is the predominating effect. The stress point therefore moves towards the boundary of the criterion. Thereafter (curve DE), the oil pressure progressively reaches its asymptotic value. Thus, the major principal stress σ_1 (equal to the oil pressure) becomes a constant, whereas the minor principal stress increases with increasing overburden pressure which now controls the evolution of the stress state. The stress path moves on a vertical line away from the criterion.

The stress state D corresponds to a critical stage in the evolution of the elementary cell, which also corresponds to a critical burial depth. This point is the most favourable for fracture initiation which can be initiated if the rock tensile strength is low enough. If not, fracture initiation will be also impossible beyond D, that is, for greater burial depths.

The boundary of the criterion has been drawn in Figure 7 for a tensile strength T = 2.5 MPa which should be compared to the threshold strength T^* = 8.82 MPa obtained previously from a reasoning in which the variation of the overburden pressure during the oil formation process was neglected. This approximation leads to overestimate the possibility of fracture initiation due to oil-pressure increase.

2 THE MACROSCOPIC APPROACH

2.1 The poroelastic modelling

In this second part of the paper, we briefly consider the main features of a mechanical modelling of primary migration at the scale of the source bed. The macroscopic modelling of the source rock as a 3-phase continuum consists in considering that $d\Omega$ is at any time the superposition of three particles, respectively constituted of rock material, oil and kerogen and located at the same macroscopic point. The rock material in $d\Omega$ constitutes the skeleton particle, the mechanical transformation of which is described by the strain tensor ε.

The variation of the mass of the kerogen particle (resp. of the oil particle) contained in $d\Omega$ when this volume is followed in the transformation of the skeleton is denoted by $m_K d\Omega$ (resp. $m_H d\Omega$) as previously. The macroscopic poroelastic modelling consists in the hypothesis that the state of the system can be defined by three state variables: the strain tensor ε, and the mass changes m_K and m_H. In particular, the total stress macroscopic tensor $\boldsymbol{S}$ and the oil pressure p_h are functions of these state variables. The non linear framework writes under differential form:

$$d\boldsymbol{S} = \boldsymbol{S}_\varepsilon : d\varepsilon + \boldsymbol{S}_H \frac{dm_H}{\rho_H} + \boldsymbol{S}_K \frac{dm_K}{\rho_K} \tag{19}$$

$$dp = \boldsymbol{P}_\varepsilon : d\varepsilon + P_H^\varepsilon \frac{dm_H}{\rho_H} + P_K^\varepsilon \frac{dm_K}{\rho_K} \tag{20}$$

Eliminating the strain tensor ε between (19) and (20), yields the variation of the oil pressure as a function of the variation of the total stress and of the kerogen and oil mass changes:

$$dp = \boldsymbol{P}_s : d\boldsymbol{S} + P_H^s \frac{dm_H}{\rho_H} + P_K^s \frac{dm_K}{\rho_K} \tag{21}$$

The above formula generalizes the relationship (11) giving p as a function of m_K, m_H and of the principal stresses S_v and S_h, previously obtained within the framework of a microscopic modelling. This suggests that the microscopic approach can be used in order to substantiate the general poroelastic modelling at the macroscopic scale.

2.2 A simplified modelling of the migration process

Let us now concentrate on the diffusion of the oil mass within the source rock. First of all, the oil mass conduction law is written under the form of the classical Darcy's law:

$$\phi(\boldsymbol{u}_H - \boldsymbol{u}_R) = \boldsymbol{k} \cdot (-\mathbf{grad}\, p + \rho_H \boldsymbol{g}) \tag{22}$$

where ϕ is the oil volume fraction, $\boldsymbol{u}_H$ and $\boldsymbol{u}_R$ denoting the velocities of the superposed oil and rock particles. The permeability of the source rock is modelled by the permeability tensor $\boldsymbol{k}$. As usual, this permeability tensor must account for the geometry of the porous network. If we adopt the hypothesis discussed in the first part of this paper, stating that the porous network consists in oil pressure induced microfractures which cross the rock matrix, $\boldsymbol{k}$ appears as a function of both the oil pressure and the local stress state. For instance, in the case of vertical microfractures, it is expected that the oil pressure has to be greater than the horizontal stress S_h in order to maintain the fractures opened. In this case, as a first approximation, it seems reasonable to search the permeability tensor in the form of a power function of the difference $p - S_h$, i.e. $\boldsymbol{k} = \boldsymbol{k_o}(p - S_h)^n$. However, the question of an appropriate modelling of the permeability tensor accounting for coupling with the macroscopic stress state and the oil pressure would certainly deserve to be more thoroughly investigated.

The oil mass balance equation expresses that the oil mass change m_K can be related to the oil mass flux and to the kerogen mass which is converted into oil. It takes the following form:

$$\dot{m}_H = -\dot{m}_K - div\left(\rho_H \phi(\boldsymbol{u}_H - \boldsymbol{u}_R)\right) \quad (23)$$

Finally, the poroelastic law provides a relationship between the oil pressure rate, the macroscopic stress rate and the oil and kerogen mass rates which is given by (21). Eliminating the oil mass rate $\dot{m}_H$ and the filtration velocity $\phi(\boldsymbol{u}_H - \boldsymbol{u}_R)$ between (21), (22) and (23) yields the evolution equation of the oil pressure:

$$\begin{aligned} \dot{p} &= P_H^s \text{div } (\boldsymbol{k} \cdot \textbf{grad}\, p) \\ &+ \dot{m}_K (P_K^s/\rho_K - P_H^s/\rho_H) + \boldsymbol{P}_s : \dot{\boldsymbol{S}} \end{aligned} \quad (24)$$

The above equation theoretically permits to determine the evolution of the oil pressure within the source bed. In addition, it shows that the oil pressure rate is the sum of a diffusion term and of two source terms. The diffusion term depends on the permeability of the porous network which is associated with the induced microfractures. The first source term is associated with the kerogen → oil transformation, and the second one with the increase of the overburden pressure. For instance, the linearization of (11) yields $\boldsymbol{P}_s : \dot{\boldsymbol{S}} = \dot{S}_V$ and $P_k^s = P_h^s = G_R/\eta$.

In this case, the first source term writes: $(G_R/\eta)(1 - \rho_K/\rho_H)\dot{m}_K/\rho_K$, which reveals that it is related to the volume expansion tendency of the kerogen → oil transformation.

CONCLUSION

In order to adress the question of oil-induced microfracturing, we have proposed under specific assumptions (plane circular kerogen flake surrounded by an homogeneous microfractured porous medium) an analytical method for the determination of the oil pressure increase. It is based on a mechanical modelling of the kerogen-oil-rock interaction at the “microscopic” scale of a kerogen particle.

It has been shown that the oil pressure tends towards an asymptotic value when the chemical transformation of kerogen is completed. The effect of the macroscopic stress variation during oil formation process proves to be negligible. However, this effect must be taken into account for describing the evolution of oil pressure at earlier stages of oil formation process.

The increase in burial depth induces an increase of oil pressure as well as a variation of the macroscopic stress which both determine the microscopic stress field. The possibility of microfracturing depends on the position of the microscopic stress state with respect to the fracture criterion. If the duration of the oil formation process is short enough, so that the macroscopic stress change associated with the corresponding (small) burial depth increase can be neglected, it is found that microfracturing is likely for the usual values of rock tensile strength. However, in the general case, neglecting the macroscopic stress change can significantly overestimate the possibility of fracture initiation due to oil-pressure increase.

The previous conclusions are valid under the specific assumptions that have been made. The present work should be extended by considering, for instance, 3D speroidal or more generally 3D ellipsoidal kerogen flake.

Considering now the “macroscopic” scale of the source bed, the evolution equation of the oil pressure has been derived within the framework of Biot's poroelasticity theory. The oil pressure rate proves to be the sum of a diffusion term which accounts for oil migration within the source bed, and of two source terms respectively associated with the volume expansion tendency of the kerogen → oil transformation and the overburden pressure increase. As far as the modelling of the macroscopic permeability is concerned, the question of oil-induced microfracturing is essential.

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