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Subcritical propagation and coalescence of oil-filled cracks: Getting the oil out of low-permeability source rocks

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[1] We use a fracture mechanics model to study subcritical propagation and coalescence of single and collinear oil-filled cracks during conversion of kerogen to oil. The subcritical propagation distance, propagation duration, crack coalescence and excess oil pressure in the crack are determined using the fracture mechanics model together with the kinetics of kerogen-oil transformation. The propagation duration for the single crack is governed by the transformation kinetics whereas the propagation duration for the multiple collinear cracks may vary by two orders of magnitude depending on initial crack spacing. A large amount of kerogen (>90%) remains unconverted when the collinear cracks coalesce and the new, larger cracks resulting from coalescence will continue to propagate with continued kerogen-oil conversion. The excess oil pressure on the crack surfaces drops precipitously when the collinear cracks are about to coalesce, and crack propagation duration and oil pressure on the crack surfaces are strongly dependent on temperature. **Citation:** Jin, Z.-H., S. E. Johnson, and Z. Q. Fan (2010), Subcritical propagation and coalescence of oil-filled cracks: Getting the oil out of low-permeability source rocks, *Geophys. Res. Lett.*, *37*, L01305, doi:10.1029/2009GL041576.

1. Introduction

[2] Black shales commonly contain significant volume fractions of kerogen, which transforms to oil and/or gas under appropriate temperature and pressure conditions. Porous flow is an unsatisfactory explanation for migration of oil out of these extremely low-permeability rocks, so fracture-induced permeability is commonly cited as the most likely mechanism [e.g., *Palciauskas and Domenico*, 1980; *Hunt*, 1990; *Law and Spencer*, 1998; *Nelson*, 2001; *Lash and Engelder*, 2005]. In this paper, we investigate the role of fluid pressure resulting from the conversion of kerogen to oil in driving subcritical propagation of cracks and the development of fracture-induced permeability.

[3] The conversion of kerogen to oil is accompanied by a significant volume increase due to the density difference between kerogen and oil. Fluid pressure will therefore increase during the kerogen-oil transformation causing local stress concentration around kerogen particles that may result in cracking of the host rock. These cracks may propagate under the excess oil pressure (the oil pressure beyond the lithostatic stress) and eventually coalesce to form interconnected fracture networks. *Ozkaya* [1988] analyzed the stresses around a kerogen particle and discussed the effect of particle shape on the orientation of fracture initiation in impermeable source rocks. *Coussy et al*. [1998] calculated the oil pressure increase during kerogen-oil conversion using a circular kerogen particle model and examined the fracture initiation around the particle. *Palciauskas and Domenico* [1980] and *Berg and Gangi* [1999] considered onset of cracking due to pore pressure buildup using a conventional strength criterion.

[4] Fracture initiation as subhorizontal, layer-parallel cracks around kerogen particles in finely laminated black shales has been observed by numerous authors [e.g., *Capuano*, 1993; *Vernik*, 1994; *Marquez and Mountjoy*, 1996; *Lash and Engelder*, 2005]. *Vernik* [1994] and *Lash and Engelder* [2005] proposed that subhorizontal cracking results from the orientation of flat kerogen particles parallel to the bedding and strength anisotropy of the source rock. *Lash and Engelder* [2005] discussed possible states of stress that may drive subhorizontal, layer-parallel crack propagation, and suggested that these cracks may connect with preexisting vertical fractures leading to vertical oil migration. *Vernik* [1994] considered a penny-shaped crack formed by kerogen-oil conversion and estimated the excess oil pressure available to initiate subhorizontal critical crack propagation.

[5] Critical propagation of a subhorizontal crack requires that the stress intensity factor equals the rock fracture toughness. However, if the crack surface excess pressure induced from kerogen-oil conversion remains at relatively low levels, then the stress intensity factor may not reach the rock fracture toughness. In this case the cracks may propagate subcritically if the stress intensity factor reaches the subcritical "threshold value" which is around 20–50% of the fracture toughness [*Atkinson*, 1984].

[6] In the present paper, we investigate subcritical propagation of a single crack as well as a series of collinear cracks driven by excess oil pressure arising from the kerogen-oil conversion. For the case of multiple crack propagation, we assume that the cracks have equal length and are periodically spaced. Natural cracks in black shale source rocks are not exactly collinear and periodically spaced [e.g., *Olson*, 2004; *Lash and Engelder*, 2005; *Ortega et al*., 2006]. However, the collinear cracks model is employed for the purpose of setting a possible lower limit on the time period required for the formation of large subhorizontal cracks that may connect with preexisting vertical fractures [*Nunn*, 1996; *Jin and Johnson*, 2008]. We also assume that the source rock is linearly elastic. Below, we first derive the fracture mechanics/finite difference formulations for subcritical propagation of oil-filled single and collinear cracks arising from the kerogen-oil

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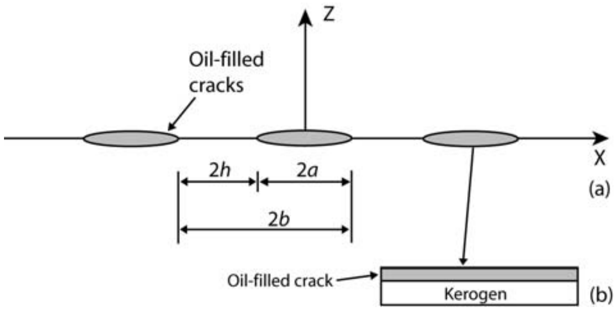

Figure 1. (a) Oil-filled, collinear, subhorizontal microcracks. (b) Microcrack formation along the top edge of a kerogen particle.

conversion. Numerical calculations are used to obtain the subcritical propagation distance and duration for a single crack, propagation duration before coalescence of the collinear cracks, and oil pressure on the crack surfaces. Effects of crack spacing and source rock temperature are also considered.

2. Theoretical Formulations

2.1. Fracture Mechanics of Collinear Cracks

[7] We consider subcritical propagation of oil-filled, horizontal collinear cracks as shown in Figure 1a. The cracks are periodically spaced with a length of $2a$ and spacing of $2h$. We note that 'crack spacing' in this paper means the separation between the two neighboring collinear crack tips. Moreover, the blade crack model instead of more realistic penny-shaped cracks is used in this study to facilitate analytical modeling and set a possible lower limit on the time period required for the formation of large subhorizontal cracks. Figure 1a shows a vertical section of the cracks in the *x-z* plane. Propagation of a single crack in a large medium can be investigated using this model by letting $h/a \rightarrow \infty$.

[8] Horizontal cracks initiate due to the volume expansion associated with the conversion of flat kerogen particles to oil [*Lash and Engelder*, 2005]. If the excess oil pressure on the crack surfaces due to the volume expansion is Δp, then the stress intensity factor at the crack tips is given by [*Sneddon and Srivastav*, 1965]

$$K_I = \Delta p \sqrt{2b \tan\left(\frac{\pi a}{2b}\right)} \tag{1}$$

where $b = a + h$. The area (or volume per unit thickness in the out-of-*xz* plane direction) of the crack is

$$V = \frac{16b^2 \Delta p(1-\nu^2)}{\pi E} \ln\left[\sec\left(\frac{\pi a}{2b}\right)\right] \tag{2}$$

Subcritical propagation occurs when the stress intensity factor is higher than the threshold value, K_{Ith}, but has not reached the rock fracture toughness, K_{Ic}. The threshold value is usually a fraction (e.g., 20–50%) of the fracture toughness, and the following power law model is commonly used to study subcritical crack growth in rocks [*Atkinson*, 1984]

$$\mathrm{v} = \frac{da}{dt} = A[K_I(a)]^n \tag{3}$$

where v is the subcritical propagation velocity, and A and n are material constants.

2.2. Kinetics of Kerogen-Oil Transformation

[9] Kerogen undergoes a complex set of reactions to form hydrocarbon in the form of oil and/or gas under appropriate pressure and temperature conditions. The transformation kinetics is described by [*Tissot et al.*, 1978; *Sweeney et al.*, 1987]

$$\frac{dV_k}{dt} = -kV_k, \quad k = B\exp\left(-\frac{E_A}{RT}\right) \tag{4}$$

where V_{k} is the kerogen volume, t time, k the kinetic rate constant, B a pre-exponential constant, E_{A} the activation energy of the transformation, R the gas constant, and T the absolute temperature. Assuming the initial volume of a kerogen particle is V_{k0}, the volume of the kerogen at time t during the conversion under constant temperature is given by

$$V_k = V_{k0}\exp(-kt) \tag{5}$$

and the volume of oil converted from the kerogen is

$$V_{oil} = [V_{k0} - V_{k0}\exp(-kt)](1+\varepsilon) = V_{k0}(1+\varepsilon)[1-\exp(-kt)] \tag{6}$$

where ε is the volume expansion rate usually in the range of 0.1 to 0.2 [*Ozkaya*, 1988]. Here we adopt the simplified approach of *Bredehoeft et al.* [1994] in which constant temperature and pressure are considered, as most of the transformation occurs near and at the final burial depth.

[10] We assume that kerogen particles have large aspect ratios and that their long dimension ($2a_0$) is oriented parallel to subhorizontal layering. We also assume that the conversion first occurs only along either the bottom or top edge, which induces an oil filled crack of length $2a_0$ along the kerogen edge as shown in Figure 1b. The basic fracture mechanics treatment remains the same as kerogen is regarded as part of the solid medium. We denote by Δp the excess oil pressure on the crack surfaces, and Δp increases gradually with increasing amount of converted oil. The pressure corresponding to the onset of subcritical crack growth can be obtained from equation (1) as follows

$$\Delta p_{th} = K_{1th} \Big/ \sqrt{2b\tan\left(\frac{\pi a_0}{2b}\right)} \tag{7}$$

The time period from the start of kerogen-oil conversion to the moment when the stress intensity factor reaches K_{Ith} can be determined using equation (6) as follows

$$t_0 = -\frac{1}{k}\ln\left[1 - \frac{V_0}{(1+\varepsilon)V_{k0}}\right] \tag{8}$$

where V_0 is the volume of the crack corresponding to Δp_{th} and is given by equation (2) with Δp replaced by Δp_{th} and a by a_0.

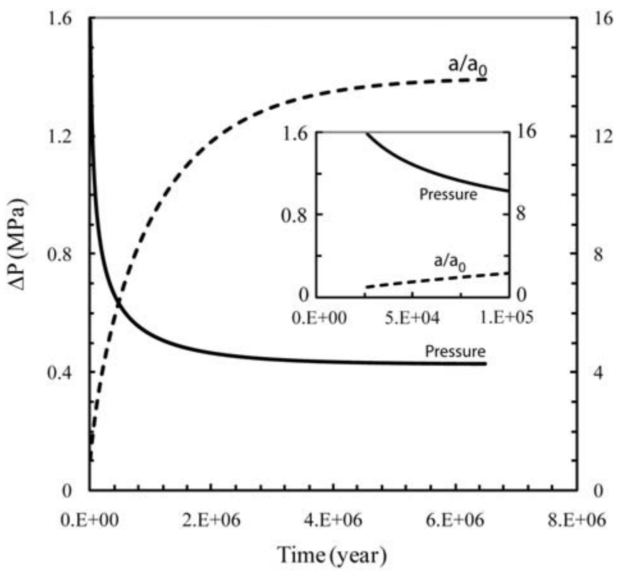

Figure 2. Excess oil pressure and crack length (a/a_0) versus time for a single crack at constant temperature of 150°C. The insert shows the evolution from $t = 0$ to 100 kyr to illustrate that crack starts at around 26 kyr.

2.3. A Finite Difference Formulation of Subcritical Crack Propagation

[11] Consider subcritical crack propagation from time t_i to t_{i+1} (i = 0, 1, 2, ..., I). The corresponding crack lengths are $2a_i$ and $2a_{i+1}$, respectively. According to the subcritical growth law, equation (3), and the stress intensity factor formula, equation (1), the crack length at t_{i+1} is

$$a_{i+1} = a_i + A(\Delta p_i)^n (2b)^{n/2}\left[\tan\left(\frac{\pi a_i}{2b}\right)\right]^{n/2}(t_{i+1} - t_i) \quad (9)$$

The volume of the crack at t_{i+1} is (see equation (2))

$$V_{i+1} = \frac{16b^2\Delta p_{i+1}(1-\nu^2)}{\pi E}\ln\left[\sec\left(\frac{\pi a_{i+1}}{2b}\right)\right] \quad (10)$$

By equating the above volume to the oil volume at t_{i+1} given in equation (6) (with t replaced by t_{i+1}), we obtain the oil pressure Δp_{i+1} at t_{i+1}

$$\Delta p_{i+1} = V_{k0}(1+\varepsilon)[1 - \exp(-kt_{i+1})] \times \frac{\pi E}{16b^2(1-\nu^2)} / \ln\left[\sec\left(\frac{\pi a_{i+1}}{2b}\right)\right] \quad (11)$$

The corresponding stress intensity factor at t_{i+1} is

$$K_{I(i+1)} = \Delta p_{i+1}\sqrt{2b\tan\left(\frac{\pi a_{i+1}}{2b}\right)} \quad (12)$$

For the crack to grow subcritically, the above stress intensity factor must be larger than K_{Ith}, or Δp_{i+1} larger than $(\Delta p_{i+1})_{th}$ given by

$$(\Delta p_{i+1})_{th} = K_{Ith}/\sqrt{2b\tan\left(\frac{\pi a_{i+1}}{2b}\right)} \quad (13)$$

Otherwise, the time t_{i+1} will be determined by

$$t_{i+1} = -\frac{1}{k}\ln\left[1 - \frac{(V_{i+1})_{th}}{(1+\varepsilon)V_{k0}}\right] \quad (14)$$

where $(V_{i+1})_{th}$ is given by equation (10) with Δp_{i+1} replaced by $(\Delta p_{i+1})_{th}$.

3. Numerical Results

[12] This section presents numerical examples of subcritical propagation distance and duration of a single crack, subcritical propagation duration and coalescence of collinear cracks, and excess oil pressure on the surfaces of the cracks during crack propagation. We also examine the effects of crack spacing and source rock temperature on subcritical crack propagation. In all calculations, we assume that the shale source rocks are impermeable and have the following properties: $E = 2.0$ GPa, $\nu = 0.4$, $K_{Ic} = 0.1$ MPa-m$^{1/2}$, K_{Ith} = 0.02 MPa-m$^{1/2}$. The parameters for subcritical fracture propagation in equation (3) are chosen as $A = 10^7$ (m/s/(MPa-m$^{1/2}$)^n) and n = 10, which results in subcritical propagation velocities of 10^{-10} m/s and 10^{-3} m/s when the stress intensity factor equals the threshold value K_{Ith} and fracture toughness K_{Ic}, respectively. The above rock properties and the subcritical propagation velocities are consistent with existing fracture studies on shales [e.g., *Nunn*, 1996; *Atkinson*, 1984]. The pre-exponential constant in the kerogen-oil transformation kinetics, equation (4), is taken as 2.8×10^{13} sec^{-1}, and the activation energy as 52400 cal/mol [*Campbell et al.*, 1978]. The source rock temperature is taken as 150°C except in Figure 4 where a temperature of 120°C is also considered. The initial flat kerogen particle is assumed to have dimensions of 100 μm and 5 μm in the (longitudinal) horizontal and vertical directions, respectively. The initial crack length is thus assumed as 100 μm. Moreover, the volume expansion rate, ε, in equation (6) is taken as 0.1 [*Ozkaya*, 1988].

[13] Figure 2 shows the crack surface excess oil pressure and crack length (a/a_0) versus time for the propagation of a single crack. As the subcritical crack propagation rate is much faster than the kerogen-oil conversion rate, the subcritical propagation distance and duration are determined primarily by the transformation kinetics, and an incremental crack surface geometry as described by *Lacazette and Engelder* [1992], and *Savalli and Engelder* [2005] would be prevail in the subcritical growth regime. Figure 2 shows that it would take about 6.5 million years for the crack to propagate from an initial length of 100 μm to approximately 1390 μm if all kerogen is assumed to convert to oil. We note that the above duration includes a period of approximately 26 kyr from the start of kerogen-oil conversion to the initiation of crack growth as the oil pressure gradually increases (see insert in Figure 2). Finally, the excess oil pressure decreases monotonically with time when the crack subcritically propagates. This is because longer cracks require lesser pressure to propagate as indicated by equation (1).

[14] Figure 3 shows the excess oil pressure and propagation of collinear cracks (nondimensional crack length a/b) versus time with two initial crack spacing values represented by b/a_0 = 2 and 3. For a given crack spacing, the

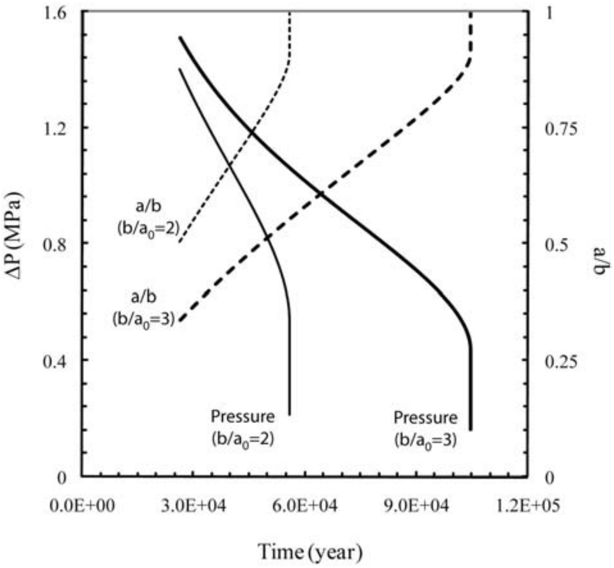

Figure 3. Effect of crack spacing on the excess oil pressure and crack propagation for collinear cracks at constant temperature of 150°C.

pressure decreases with time and drops precipitously when the cracks are about to coalesce. The oil pressure required to subcritically grow the cracks is higher for larger crack spacing than for smaller spacing although the initial crack lengths are the same (100 μm). For example, the pressures corresponding to the onset of crack propagation are 1.41 MPa and 1.52 MPa for $b/a_0 = 2$ and 3, respectively. The reduced oil pressure for closer spaced cracks is a direct result of crack interaction. Furthermore, for a given crack spacing, the crack length $2a$ increases with time as expected. Crack coalescence occurs at about 56 kyr for $b/a_0 = 2$ and about 105 kyr for $b/a_0 = 3$ when the crack propagation distance equals the half ligament length ($b - a_0$). Crack propagation accelerates at the final growth stage when the stress intensity factor increases rapidly with decreasing ligament length as indicated in equation (1). Therefore crack spacing has a significant effect on the crack propagation duration required to form coalesced macroscopic cracks. We also note that the cracks start to propagate after about 26 kyr when the oil pressure becomes high enough to induce a stress intensity factor equal to the threshold K_{Ith} and the total propagation duration includes the above initiation period.

[15] Figure 4 shows the effects of source rock temperature on the propagation of collinear cracks and excess oil pressure. The crack spacing is chosen as $b/a_0 = 3$. Equation (4) indicates that the kerogen-oil conversion rate increases with increasing temperature. Hence, the crack propagation duration before coalescence will become longer for source rocks at lower temperatures. Figure 4 shows that it takes about 12.2 m.y. (which includes about 3.03 m.y. for initiating crack growth) for the cracks to coalesce for a rock temperature of 120°C, which is two orders of magnitude longer than that for the 150°C source rock (105 kyr, also shown in Figure 3). Figure 4 also shows that although the oil pressure required to initiate crack growth remains the same at the lower temperature, it takes much longer time for the oil pressure to reach the critical value for the 120°C source rock.

4. Discussion and Conclusions

[16] Our analysis and calculations show that the propagation duration for a single oil-filled crack is governed by the transformation kinetics. All kerogen would convert to oil when the crack ceases to propagate and this process may well take several million years for a 150°C source rock. For periodically spaced collinear cracks the crack propagation duration may be reduced by two orders of magnitude due to crack interactions. The oil pressure on the crack surfaces decreases monotonically with time during crack propagation, but decreases precipitously when the collinear cracks are about to coalesce. Moreover, a large amount of kerogen (95.9% of original kerogen volume for $b/a_0 = 2$, and 92.5% for $b/a_0 = 3$) still remains unconverted when the collinear cracks coalesce. The continued kerogen-oil conversion is therefore likely to facilitate significant additional propagation of the connected cracks (the current collinear cracks model may be approximately applied to a series of finite cracks). Crack coalescence to form macroscopic cracks increases the possibility for the cracks to connect with preexisting vertical fractures thereby facilitating vertical oil migration out of the low-permeability source rock.

[17] This work focuses on the effects of initial kerogen spacing and source rock temperature on the subhorizontal migration of oil through subcritical crack propagation. Physical and material parameters also significantly influence the oil migration/subcritical crack propagation behavior. For example, higher Young's modulus E, lower threshold stress intensity K_{Ith}, and higher volume expansion rate of kerogen ε would shorten the crack propagation duration as seen from equations (11)–(14). The subcritical crack propagation parameters, however, only influence the final crack propagation stage near coalescence when the propagation velocity exceeds that corresponding to K_{Ith}.

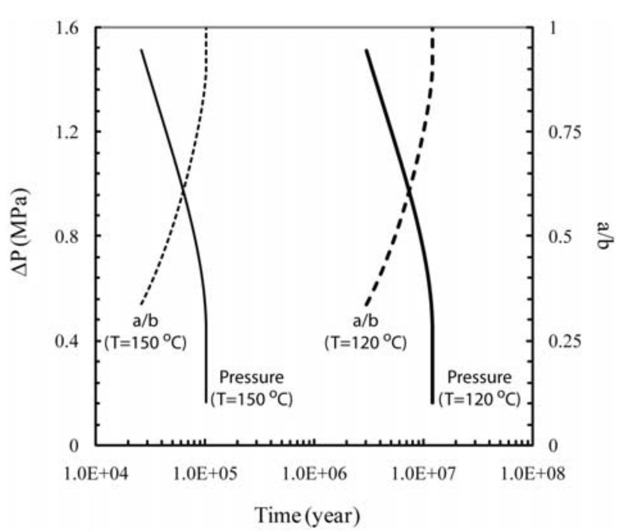

Figure 4. Effect of source rock temperature on the excess oil pressure and crack propagation for collinear cracks with initial crack spacing $b/a_0 = 3$.

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