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Primary oil migration through buoyancy-driven multiple fracture propagation: Oil velocity and flux

Z.-H. Jin¹ and S. E. Johnson²

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[1] We present a fracture-mechanics-based formulation to investigate primary oil migration through the propagation of an array of periodic, parallel fractures in a sedimentary rock with elevated pore fluid pressure. The rock is assumed to be a linearly elastic medium. The fracture propagation and hence oil migration velocity are determined using a fracture mechanics criterion together with the lubrication theory of fluid mechanics. We find that fracture interactions have profound effects on the primary oil migration behavior. For a given fracture length, the mass flux of oil migration decreases dramatically with an increase in fracture density. The reduced oil flux is due to the decreased fracture propagation velocity as well as the narrowed fracture opening that result from the fracture interactions.
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1. Introduction

[2] Black shales deposited in basins commonly contain significant volume fractions of solid organic material. As these sediments undergo progressive burial, some of the organic matter is converted to kerogen. With increasing temperature, the kerogen undergoes a complex set of reactions to form hydrocarbon. If the sediments contain high enough concentrations of sapropelic kerogen, they will generate a large volume of oil during the early stages of thermal maturation. As oil saturation increases, the relative permeability of oil increases dramatically and the stage is set for expulsion (primary migration) from the source to overlying carrier rocks.

[3] Although the specific mechanisms dominantly responsible for primary migration are debated, it is generally accepted that high pore fluid pressure in the source rock provides the principal driving force in many or most petroleum fields [e.g., Durand, 1983; Law and Spencer, 1998]. Evidence from petroleum fields around the world indicates that the overpressured source rocks are typically organic-rich shale characterized by extremely low permeability, and so porous flow governed by Darcy's law provides an unsatisfactory explanation for primary migration in many instances. Other mechanisms such as molecular diffusion and migration in solution with water are typically considered as negligible contributors owing to

the low solubility of oil in water [England *et al.*, 1987; Durand, 1983; Hunt, 1996].

[4] Owing to the shortcomings of other expulsion mechanisms, many published papers invoke fracture permeability as the most likely mechanism for transferring petroleum from source to carrier rocks [e.g., Palciauskas and Domenico, 1980; Hunt, 1990; Miller, 1995; Law and Spencer, 1998; Nelson, 2001; Lash and Engelder, 2005]. Intact samples from source rocks commonly show bitumen-bearing fractures of variable width up to several mm [e.g., Hunt, 1990; Nelson, 2001; Lash and Engelder, 2005], so there is clear evidence that fracture permeability plays a role in primary oil migration.

[5] Nunn [1996] considered buoyancy-driven propagation of fractures that form as the result of overpressure in the fluid-saturated source and showed that primary oil migration via fracture propagation can be significant. Nunn [1996] derived the formulas of fracture propagation velocity and average fracture opening for the propagation of a single fracture and calculated mass flux of oil by multiplying the flux of the single fracture by the fracture density. The interactions between the multiple fractures were not treated in Nunn's study. Dahm [2000] predicted a lower fracture propagation velocity than Nunn [1996] by using the same physical parameters but a modified fluid flow law.

[6] The present work investigates the effect of multiple fracture interactions on primary oil migration through buoyancy-driven fracture propagation. Following Nunn [1996], we adopt the assumptions that the sediment is linearly elastic, the oil-filled fractures are parallel in the vertical direction and have equal length, and the fractures propagate at a constant velocity (steady state propagation). We further assume that the fractures are periodically distributed so that a two-dimensional (2D), semi-analytical approach becomes applicable. We use an integral equation method to derive the expressions for fracture opening displacement, fracture propagation velocity, and mass flux of oil migration. Numerical results are presented to quantitatively illustrate the effect of fracture interactions on the propagation velocity and mass flux of oil.

2. An Oil-Driven Multiple Fracture Propagation Model

2.1. Fracture Surface Pressure

[7] Vertical propagation of oil-driven fractures is expected owing to buoyancy and the typically subhorizontal orientation of the least compressive stress in most sedimentary basins. However, they may also propagate along mechanically anisotropic layering such as bedding in finely laminated shales [e.g., Lash and Engelder, 2005]. For simplicity, we consider flow of oil through an array of parallel vertical fractures as shown in Figure 1 where $2a$ is

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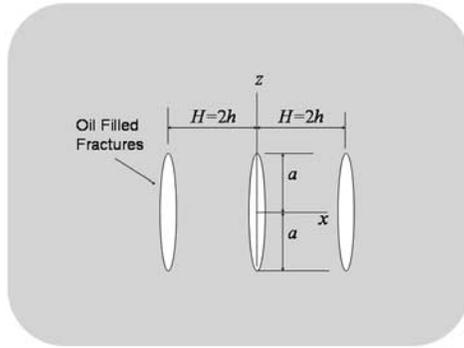


Figure 1. Oil-filled, periodic, parallel fractures in vertical z -direction.

the length of the fractures in vertical direction and $H = 2h$ is the fracture spacing; our method can be extended to evaluate variable orientations and the effects of mechanical anisotropy. We assume that the size of these fractures in the perpendicular direction to the x - z plane is large so that a two-dimensional (2D) plane strain model [Nunn, 1996; Bai and Pollard, 2001] can be used. Figure 1 thus shows a vertical section of these ‘blade’ fractures in the x - z plane. Oil flow in the fractures is described by the lubrication theory in which the fluid flux and pressure follow the relationship of Poiseuille flow. In general, problems of oil flow and fracture propagation are coupled so that oil pressure, stress field, fracture surface profile and fracture propagation velocity interact with each other and must be determined simultaneously. However, for slow oil flow and fracture propagation a simplified approach used by Weertman [1971] and Nunn [1996] can be employed. In this approach, the net (or excess) pressure, p_{net} , on the fracture surface due to oil buoyancy, oil flow within the fractures and confining pressure is described by a linear function

$$p_{net}(z) = p_0 + p_1 z \quad (1)$$

where p_0 is the net pressure at the fracture center ($z = 0$), p_1 the net pressure gradient, and z the upward coordinate with the lower and upper fracture tips at $z = -a$ and $z = a$, respectively, where a is the half fracture length. In equation (1), p_0 and p_1 are determined using a fracture mechanics criterion at the fracture tips.

[8] For oil-filled steady state fracture propagation, the fracture length and fracture profile remain unchanged [Nunn, 1996]. This requires that the lower fracture tip closes during propagation. In fracture mechanics, these conditions are described by

$$K_I(a) = K_{Ic}, K_I(-a) = 0 \quad (2)$$

where $K_I(a)$ and $K_I(-a)$ are the stress intensity factors at the upper and lower tips, respectively, and K_{Ic} the fracture toughness of the host rock.

[9] For the parallel fractures under the net fracture surface pressure in equation (1), the stress intensity factors have the following forms

$$\begin{aligned} K_I(a) &= p_0 \sqrt{\pi a} F_I^0(h/a) + p_1 a \sqrt{\pi a} F_I^1(h/a), \\ K_I(-a) &= p_0 \sqrt{\pi a} F_I^0(h/a) - p_1 a \sqrt{\pi a} F_I^1(h/a) \end{aligned} \quad (3)$$

where h is the half fracture spacing, and $F_I^0(h/a)$ and $F_I^1(h/a)$ are nondimensional, fracture-spacing-dependent parameters to be determined in the following subsection. Substituting equation (3) into equation (2) and solving the resulting equations for p_0 and p_1 , we have

$$p_0 = \frac{K_{Ic}}{2\sqrt{\pi a} F_I^0(h/a)}, p_1 = \frac{K_{Ic}}{2a\sqrt{\pi a} F_I^1(h/a)} \quad (4)$$

[10] The above simplified approach assumes no oil flow from the host rock into the fractures, which means either that the fracture surfaces are impermeable, or that no fluid pressure gradient exists across the fracture surfaces. The method is only approximate, but it facilitates semi-analytical treatment of the problem. It is also consistent with the assumptions that fracture length remains constant during propagation and that the host rock is approximated as an elastic, not poroelastic, medium. The above formulation also assumes simultaneous propagation of the parallel fractures. Although difficult to demonstrate in nature, simultaneous growth of parallel cracks is common in ceramics when subjected to thermal gradients [Geyer and Nemat-Nasser, 1982].

2.2. Fracture Mechanics Formulation

[11] The fracture-spacing-dependent parameters in equations (3) and (4) are determined by fracture mechanics analysis. The fractures are modeled as oil filled, plane strain cracks in an infinite space. A singular integral equation method is used to analyze the fracture propagation problem. Because the fracture propagation velocity is much smaller than the wave speed of the host rock [Nunn, 1996], the inertia effect can be ignored and the problem becomes quasi-static. The basic integral equation has the following form

$$\int_{-1}^1 \left[\frac{1}{s-r} + ak(r,s) \right] \varphi(s) ds = -\frac{2\pi(1-\nu^2)}{E} (p_0 + p_1 ar), |r| \leq 1 \quad (5)$$

where E is Young’s modulus, ν Poisson’s ratio, $r = z/a$, $\varphi(z)$ the unknown density function

$$\varphi(z) = (\partial u_x / \partial z)|_{x=0} \quad (6)$$

with $u_x(z, x)$ being the displacement perpendicular to the crack, and $k(z, z')$ a known Fredholm kernel.

[12] The unknown function $\varphi(r)$ may be expressed in the following normalized form

$$\varphi(r) = \frac{1-\nu^2}{E} \left[p_0 \tilde{\varphi}^{(0)}(r) + p_1 a \tilde{\varphi}^{(1)}(r) \right] \quad (7)$$

[13] Once the solution of the above integral equation is solved, the stress intensity factors at the fracture tips can be calculated from

$$\begin{aligned} K_I(a) &= -\frac{1}{2} \sqrt{\pi a} \left[p_0 \tilde{\psi}^{(0)}(1) + p_1 a \tilde{\psi}^{(1)}(1) \right], \\ K_I(-a) &= \frac{1}{2} \sqrt{\pi a} \left[p_0 \tilde{\psi}^{(0)}(-1) + p_1 a \tilde{\psi}^{(1)}(-1) \right] \end{aligned} \quad (8)$$

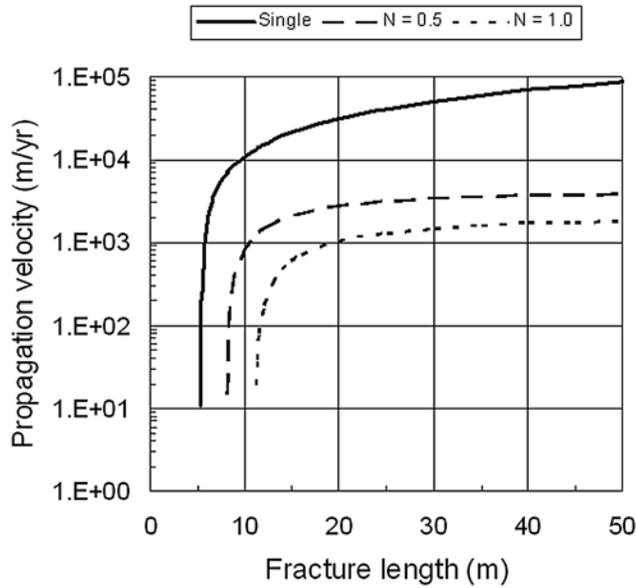


Figure 2. Fracture propagation velocity versus fracture length (in vertical z-direction) for various values of fracture density.

where $\tilde{\psi}^{(i)}$ are related to $\tilde{\varphi}^{(i)}$ by

$$\tilde{\psi}^{(i)}(r) = \sqrt{1-r^2} \tilde{\varphi}^{(i)}(r), \quad i = 0, 1 \quad (9)$$

[14] Comparing equations (8) and (3) and considering symmetry conditions for $\tilde{\psi}^{(i)}(r)$, we have

$$F_I^0(h/a) = -\frac{1}{2} \tilde{\psi}^{(0)}(1), F_I^1(h/a) = -\frac{1}{2} \tilde{\psi}^{(1)}(1) \quad (10)$$

[15] Besides the stress intensity factor, the fracture surface opening displacement is also an important physical quantity which can be calculated from

$$\delta(r) = \frac{1-\nu^2}{E} [p_0 \tilde{\delta}^{(0)}(r) + p_1 a \tilde{\delta}^{(1)}(r)] \quad (11)$$

where

$$\tilde{\delta}^{(i)}(r) = -2a \int_r^1 \tilde{\varphi}^{(i)}(s) ds = -2a \int_r^1 \frac{\tilde{\psi}^{(i)}(s)}{\sqrt{1-s^2}} ds, i = 0, 1 \quad (12)$$

2.3. Fracture Propagation Velocity and Oil Migration Flux

[16] Following Nunn [1996], the fracture propagation velocity, V , is approximately determined using the relationship of Poiseuille flow as follows

$$V = \frac{\delta_{ave}^2}{12\eta} (\Delta\rho g - p_1) \quad (13)$$

where δ_{ave} is the average separation of the two fracture surfaces defined by

$$\delta_{ave} = \frac{1}{2a} \int_{-a}^a \delta(z) dz = \frac{1-\nu^2}{2aE} \int_{-1}^1 [p_0 \tilde{\delta}^{(0)}(r) + p_1 a \tilde{\delta}^{(1)}(r)] dr \quad (14)$$

η the oil viscosity, g the gravitational acceleration, $\Delta\rho = \rho_{rock} - \rho_{oil}$, ρ_{rock} the rock density, ρ_{oil} the oil density, and p_0 and p_1 given in equation (4).

[17] The mass flux of oil migration, f , is defined as the mass of oil that flows across a unit horizontal area per unit time. The fracture density, N , is defined as the number of fractures in a horizontal meter. For the periodic, parallel fractures with a spacing of H , $N = 1/H$. After the fracture propagation velocity and the average fracture opening are determined, we can calculate the mass flux of oil migration by [Nunn, 1996]

$$f = 2a\delta_{ave} V \rho_{oil} N \quad (15)$$

3. Numerical Results

[18] This section presents numerical examples to illustrate effects of fracture density on the oil migration velocity and mass flux. In all calculations, we use the following properties for the sedimentary rock and oil [Nunn, 1996]: $E = 2.215$ GPa, $\nu = 0.42$, $K_{Ic} = 0.1$ MPa-m^{1/2}, $\rho_{rock} = 2150$ kg/m³, $\rho_{oil} = 840$ kg/m³, and $\eta = 0.01$ Pa-s. Although oil velocities are inversely proportional to viscosity, which can vary more than two orders of magnitude depending on subsurface temperature and pressure conditions [e.g., England et al., 1987; Hayba and Bethke, 1995], we ignore this effect here in order to focus on the role of fracture interaction.

[19] Figure 2 shows the fracture propagation (or oil migration) velocity versus fracture length for two values of fracture densities: $N = 0.5$ and 1. The results for the single fracture problem are also included. For a given fracture density, there is a critical fracture length below which the fractures do not propagate critically; however, the fracture may propagate subcritically [Atkinson, 1984]. The fractures will propagate when they become longer than the critical length, and the longer the fractures, the higher the velocity. The propagation velocity increases dramatically for fracture lengths just larger than the critical size and levels off for longer multiple fractures. The fracture density significantly affects the propagation velocity. For a given fracture length, the velocity becomes significantly lower for the multiple fractures with increasing fracture density. For example, the velocity is about 31,544 m/year for the single fracture of 20 meters long. The velocity decreases to 2768 m/year and 1028 m/year for multiple fractures with densities of $N = 0.5$ and 1, respectively, which represents an order of magnitude reduction.

[20] The fracture spacing to fracture length ratios of $H/(2a) = 1/50$ ($N = 1$) and $2/50$ ($N = 0.5$) considered in the present study are within the range of 0.02 and 10 for natural parallel fractures discussed by Germanovich and Astakhov

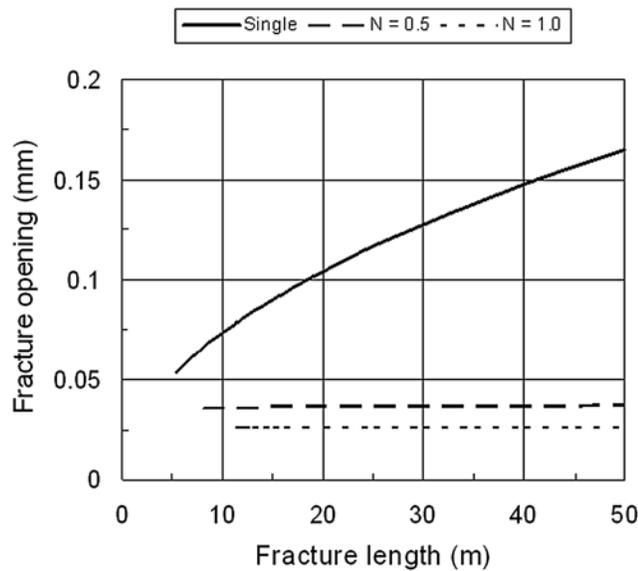


Figure 3. Average fracture opening versus fracture length (in vertical z-direction) for various values of fracture density.

[2004]. However, in the ‘stress shadow’ theory discussed by *Fischer et al.* [1995], the fracture spacing to length ratio can not reach the lower values (on the order of 0.01) in the above spacing range. This is probably because the stress shadow theory typically does not consider interactions between fractures. The stress shadow may become smaller if fracture interactions are considered thereby allowing smaller fracture spacing.

[21] Figure 3 shows the average fracture opening versus fracture length for two values of fracture densities: $N = 0.5$ and 1, and the corresponding results for the single fracture. Again, the effect of fracture density is significant. Whereas the opening of the single fracture increases dramatically with increasing fracture length, the opening for the multiple fractures is relatively insensitive to the fracture size. Moreover, the opening for the single fracture is significantly higher than those for the multiple fractures. For example, the opening is 0.104 mm for a single fracture of 20 meters long. The corresponding openings for the multiple fractures with fracture densities of $N = 0.5$ and 1 are only about 0.037 mm and 0.026 mm, respectively.

[22] The reduced propagation velocity and fracture opening for multiple fractures lead to lower mass flux of oil migration as indicated by equation (15). Figure 4 shows the mass flux of oil migration as a function of fracture length for the two values of fracture densities considered: $N = 0.5$ and 1. *Nunn* [1996] also calculated the oil flux through parallel fractures but did not consider the effect of fracture interactions on the propagation velocity and fracture opening. It is clear from Figure 4 that ignoring the multiple fracture interactions results in overestimated mass flux of oil migration. For example, the mass fluxes for fractures of length 20 meters with densities of $N = 0.5$ and 1 are calculated as 27,611 and 55,222 kg/m²/year, respectively, without considering the fracture interactions. The fluxes decrease by two orders of magnitude to 856 and 452 kg/m²/year, respectively,

when the effects of fracture interactions are included. Furthermore, the mass flux decreases with an increase in fracture density based on the present interaction theory, whereas the flux increases linearly with fracture density using the single fracture method of *Nunn* [1996]. *Philip et al.* [2005] recently investigated fluid flow in geomechanically simulated fracture networks and showed that although the fracture permeability is highly sensitive to fracture aperture, it is more sensitive to fracture patterns and connectivity.

4. Discussion and Conclusions

[23] Using a periodic parallel fractures model and linear elastic fracture mechanics, we show that the propagation velocity of oil-filled fractures is significantly lower for multiple fractures with increasing fracture density. The fracture opening for the multiple fractures is also significantly smaller than that for the single fracture. The reduced propagation velocity and fracture opening for multiple fractures lead to significantly lower mass flux during primary oil migration.

[24] Our study assumes steady state fracture propagation and periodic distribution of parallel fractures. Although fracture propagation in the oil environment is typically a transient process [*Savalli and Engelder*, 2005], it is generally believed that the transient and steady state solutions are on the same order of magnitude. Natural parallel fractures may not be periodically spaced [*Fischer et al.*, 1995; *Olson*, 2004]. However, periodicity is a reasonable approximation in that it captures the fundamental fracture-spacing effects. For example, *Germanovich and Astakhov* [2004] assumed periodicity to study the permeability of a set of parallel joints, and *Bai and Pollard* [2001] examined a number of equally spaced fractures to investigate the fracture spacing effect on fracture aperture and fluid flow rate. Non-periodicity of fracture spacing will affect the fracture propagation velocity and fluid flux. Moreover, natural parallel fractures

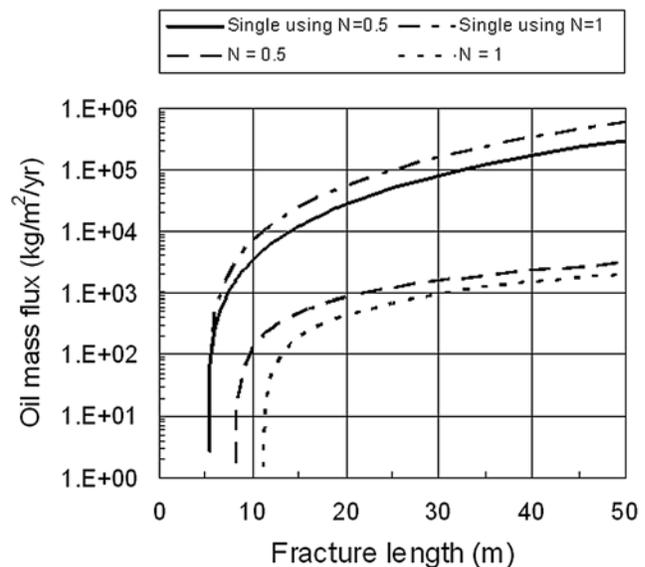


Figure 4. Oil mass flux versus fracture length (in vertical z-direction) for various values of fracture density.

may have different size [Ortega *et al.*, 2006], which will affect fracture patterns, propagation velocity and oil flux.

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