Topography- and fracture-driven fluid focusing in layered ocean sediments

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[1] Upward fluid flow is often invoked to explain the occurrence of methane hydrate in ocean sediments, whereas one‐dimensional compaction models predict downward flow relative to the seafloor. Explaining the presence of upward flow requires a more complete compaction model. We develop a two‐dimensional model of compaction‐driven flow to quantify the focusing of pore fluids by topography and fractures when sediments have anisotropic permeability. We use a bulk anisotropic permeability to capture the effects of lithologic layering when the grid spacing is too coarse to resolve individual layers. Even small slopes (10°) in bedding planes produce upward fluid velocity, with focusing becoming more effective as slopes increase. Additionally, focusing causes high excess pore pressure to develop below topographic highs, promoting high‐angle fracturing near the crest. Magnitudes of upward pore fluid velocity are much larger in fractured zones, particularly when the surrounding sediment matrix is anisotropic in permeability. Enhanced flow of methane‐bearing fluids from depth provides a simple explanation for preferential accumulation of hydrate under topographic highs. Citation: Frederick, J. M., and B. A. Buffett (2011), Topography‐ and fracture‐driven fluid focusing in layered ocean sediments, Geophys. Res. Lett., 38, L08614, doi:10.1029/2010GL046027.

1. Background

[2] Methane hydrate, a frozen mixture of water ice and methane gas, has been found within ocean sediments along continental margins. Its formation is controlled by many factors, such as thermodynamic conditions and the availability of methane gas. Most of the methane is produced by biogenic conversion of organic matter present in the sediments [Kvenvolden, 1998]. Many studies have invoked upward fluid flow to explain the observed abundance of hydrate [Hyndman and Davis, 1992; Xu and Ruppel, 1999; Égeberg and Dickens, 1999; Ruppel and Kinoshita, 2000; Pecher et al., 2001; Davie and Buffett, 2003]. Moreover, the occurrence of hydrate appears to be correlated with the lithology, implying an influence of physical properties such as the grain size [Malinverno, 2010] or permeability [Weinberger et al., 2005; Tréhu et al., 2006; Torres et al., 2008] on hydrate formation. There is also evidence that many deposits seem to preferentially accumulate beneath topographic highs [Fink and Spence, 1999; Paull et al., 2000]. Based on these observations, pore fluid focusing due to topography or high‐angle fractures have been proposed as ways to supply additional methane into the hydrate stability zone [Pecher et al., 2001; Weinberger and Brown, 2006; Cook et al., 2008]. The goal of this study is to quantitatively assess the feasibility of these mechanisms.

2. Compaction‐Driven Fluid Flow Model

[3] When sediments settle onto the ocean floor with a sedimentation rate \( \dot{S} \), fluid is trapped between the particles. As the sediments become compacted due to the weight of overlying layers, the porosity \( \phi \) is reduced, causing some of the trapped pore fluid to be expelled, much like squeezing a sponge saturated with water. The porosity profile with depth (y increasing) is often described empirically by Athy’s Law [Athy, 1930] as

\[
\phi(y) = \phi(0)e^{-y/L}
\]

where \( \phi(0) \) is the sediment porosity at the seafloor and \( L \) is the characteristic length scale for compaction. Sediment permeability often depends on porosity, and can be described by a modified Kozeny–Carman relation [Mavko and Nur, 1997] (see auxiliary material).¹

[4] The equations that describe compaction‐driven flow are derived from conservation principles for both the sediments and water. With the assumption that the fluid and solid are incompressible, and that the porosity profile with depth is steady relative to the seafloor, the equations simplify to

\[
\nabla \cdot (v_s(1 - \phi)) = 0
\]

\[
\nabla \cdot (v_f \phi) = 0
\]

where \( v_s \) and \( v_f \) are the sediment and fluid interstitial velocity, respectively. Equations (2) and (3) can be integrated for \( v_s \) and \( v_f \) in a reference frame fixed to the seafloor, assuming that the velocities are only a function of depth, and that \( v_s = v_f \) at a depth \( D \) where the fluid is immobile. \( D \) is approximated by the sediment thickness above the basement oceanic crust at Blake Ridge, roughly 4 km [Tuckholme et al., 1982]. The one‐dimensional solution is

\[
v_s(y) = \frac{\dot{S}(1 - \phi(0))}{1 - \phi(y)}
\]

\[
v_f(y) = \frac{v_s(D)\phi(D)}{\phi(y)}
\]

¹Auxiliary materials are available in the HTML. doi:10.1029/2010GL046027.
Both the sediment and fluid velocity are positive, meaning the direction of flow is downward relative to the seafloor. This flow carries dissolved methane downwards through the hydrate stability zone. Because the methane solubility increases with depth in the stability zone [Davie et al., 2004; Sun and Duan, 2007], the fluid becomes increasingly under-saturated in methane. This would inhibit formation or lead to dissolution of hydrate (if present) without additional sources of methane (e.g. biogenic production). Conversely, upward flow promotes hydrate formation by supplying methane from below the stability zone.

### 3. Anisotropy in Darcy’s Law

Anisotropy in sediment permeability can arise in many ways. A typical cause is due to variations in lithology. Distinct sedimentary layers with different permeability can produce a strong anisotropy in the bulk permeability. Often, bulk permeability along the bedding layers (K_b) is 100 or 1000 times larger than across the bedding layers (K_a) [Phillips, 1991]. The presence of fractures can also introduce anisotropy by enhancing the permeability in the direction of fracture. When fluid is expelled from the sediment pore space into the surroundings due to compaction, the fluid flux \( q_c \), or transport velocity, is described by Darcy’s Law

\[
q_c \equiv \phi (v_f - v_s) = -\frac{K}{\mu} \nabla P^* \tag{6}
\]

which is valid for incompressible and laminar flow through a porous media. Bulk sediment permeability is described by \( K \) which is a tensor when permeability is anisotropic. The gradient in excess (or non-hydrostatic) pore pressure \( \nabla P^* \) due to sediment loading drives the flow of fluid with a viscosity \( \mu \). Rearranging (6) for the velocity of the pore fluid relative to the seafloor gives \( v_f = q_c/\phi + v_s \). The direction of \( v_s \) depends on the competition between the upward fluid flux, \( q_c \), and the downward movement of sediments, \( v_s \). Many mechanisms can cause \( q_c/\phi \) to locally exceed \( v_s \). Some examples include the dehydration reactions of clays [Colten-Bradley, 1987], a decreasing sedimentation rate in time [Hyndman and Davis, 1992], or an increase in pore pressure at the base of the stability zone due to hydrate dissociation during burial [Xie and Germanovich, 2006]. Upward migration of free gas due to buoyancy may also increase methane flux [Liu and Flemings, 2007]. In this study, we investigate topography- and fracture-driven pore fluid focusing as mechanisms to cause upward velocity. If sediment layers are sloped due to topography, a preferential flux \( q_c \) along the bedding layers may focus fluid into topographic highs. Furthermore, the topography itself may promote fractures [Rowe and Gettrust, 1993], creating enhanced permeability pathways towards the seafloor. If either of these two mechanisms cause \( q_c/\phi \) to locally exceed \( v_s \), upward flow relative to the seafloor is possible.

### 4. Numerical Model

To characterize the conditions for upward fluid flow, we apply a numerical model based on the finite volume method for the excess pore pressure distribution. Blake Ridge, a well-studied gas hydrate province along the east coast of North America, motivates our choice of physical parameters (see Table 1).

A no-flux boundary condition is enforced at depth \( D \), while the excess pore pressure at the seafloor \((z=0)\) is set to zero. The excess pore pressure is governed by

\[
\nabla \left\{ -\frac{K}{\mu} \nabla P^* \right\} - \nabla \cdot \left\{ \phi (v_f - v_s) \right\} = 0 \tag{7}
\]

which is obtained from the divergence of (6). The second term in (7) represents the source of compaction flux, which can be written entirely in terms of \( v_s \) using (2) and (3) as

\[
\nabla \cdot \left\{ -\frac{K}{\mu} \nabla P^* \right\} - \nabla \cdot v_s = 0 \tag{8}
\]

The sediment velocity is expressed in terms of the observed porosity using (4). The solution for \( P^* \) is then used to calculate \( q_c \) from (6), and the pore fluid velocity relative to the seafloor is obtained from the expression \( v_f = q_c/\phi + v_s \). An average sedimentation rate of 0.16 mm yr\(^{-1}\) from Blake Ridge is assumed for all cases [Paul et al., 2000]. We do not allow for feedback on the porosity profile with depth due to pore pressure changes.

Anisotropy in the sediment permeability is described with a ratio of horizontal to vertical permeability \( K_b/K_a \). The permeability along a fractured zone is similarly described by the ratio \( K_f/K_a \). Topography in the sediments is modeled as a cosine wave with height \( h(x) = h \cos kx \) and wave number \( k \). The slope of the sediment layers follow the topography at all depths. Therefore, the local angle of the bedding planes

\[
\theta = \frac{dh}{dx} = -kh \sin kx \tag{9}
\]

is used to rotate the permeability tensor \( K \) from the frame of the bedding planes into the frame of the computations. The resulting off-diagonal terms in \( K \) couple the horizontal and vertical components of flow.

### 5. Results

Topography causes focusing of pore fluid when the permeability permits preferential flow along bedding layers.
For all slopes in bedding planes, focusing can produce upward pore fluid velocities relative to the seafloor beneath the topographic high. However, larger slopes produce more effective focusing, thus producing larger magnitudes in upward fluid velocity than shallower slopes. Figure 1b shows the pore fluid velocity profile relative to the seafloor at a depth of 500 mbsf. The maximum slope in bedding planes varies from 10° to 30°. Wavelength of topography is 4 km.

For all slopes in bedding planes, focusing can produce upward pore fluid velocities relative to the seafloor beneath the topographic high. However, larger slopes produce more effective focusing, thus producing larger magnitudes in upward fluid velocity than shallower slopes. Figure 1b shows the pore fluid velocity profile relative to the seafloor across a sediment depth of 500 mbsf (roughly the base of the hydrate stability zone at Blake Ridge [Paul et al., 2000]). Even for small slopes in bedding planes (10°), a maximum upward velocity of 0.010 mm yr\(^{-1}\) at the BSR is predicted directly beneath the ridge crest. For a 30° slope, the maximum velocity increases to 0.097 mm yr\(^{-1}\) at a location that is shifted from the ridge axis toward the flanks. The location of maximum velocity shifts towards the region where the slope of the bedding planes in largest.

Moreover, pore fluid focusing due to sloped bedding planes creates lateral variations in excess pore pressure distribution beneath the topographic high. For all slopes in bedding planes, excess pore pressure is elevated beneath the ridge crest relative to the flanks (see Figure 1a). In regions of topography where the maximum principle stress is oriented vertically, elevated excess pore pressure along the ridge axis can promote tensional failure due to the reduction in effective stress [Sibson, 1981]. This pressure anomaly is amplified as the slope in bedding planes increases, and may tend to aid near-vertical fracturing, thereby producing a stress-induced increase in the vertical permeability of the sediments [Bruno, 1994].

Enhancing vertical sediment permeability, due to the presence of high-angle fractures, is an efficient way of focusing pore fluids and produces strong upward fluid advection. The strength of advection depends on the ratio of the vertical fracture permeability to the vertical matrix permeability (\(K_v'/K_v\)), as well as how easily fluid can be tapped from the surrounding matrix (ie. \(K_h/K_v\)). For example, as the ratio \(K_v'/K_v\) increases, the amount of fluid focused into the fractured zone (and hence \(v_f\)) increases. However, once \(K_v'/K_v\) becomes large (>1000), \(v_f\) no longer increases, and focusing is ultimately limited by the amount of fluid that can be supplied from the surrounding sediment matrix (see Figure 2). The ease of tapping pore fluids from the surrounding sediments is affected by the permeability structure. For example, an anisotropic sediment matrix (\(K_h/K_v = 100\)) can produce an upward fluid velocity within the fractured zone which is almost 4 times larger than an isotropic sediment matrix (\(K_h/K_v = 1\)), as shown in Figure 2. This is because anisotropic sediments enhance lateral fluid migration to the fracture.

The area of the seafloor which is fractured is also an important control on fluid velocity. From the viewpoint of...
mass conservation, the Darcy flux \( q \), taps a finite amount of fluid that is squeezed from the sediments due to \( \nabla \cdot v \). If the width of the fractured zone is small, transport velocities through it will be higher than through wider fractured zones. When the entire domain is fractured (say \( K_{v} = K \), everywhere), the medium is effectively homogeneous, thus no upward flow is expected.

### 6. Discussion and Conclusion

[14] Our numerical model predicts that topography-driven fluid focusing can produce upward fluid velocity relative to the seafloor. Previously publishedhydrate studies can give insight to its relative significance at specific locations. For example, in order to match observed bromide and iodide profiles in the sediment at Blake Ridge, Egeberg and Dickens [1999] require an upward fluid velocity of 0.08 mm yr\(^{-1}\) at the seafloor. Upward fluid velocity at 500 mbsf would need to be roughly 10% larger than those at the seafloor in order to account for a decrease in porosity with depth. Our model predicts a maximum upward fluid velocity of 0.097 mm yr\(^{-1}\) when bedded planes slope at 30° and sediment permeability is anisotropic (\( K_{v}/K_{h} = 100 \)). Based on these results, it is unlikely that topography-driven fluid focusing acting alone is an effective mechanism at Blake Ridge, where slopes are much smaller. However, stronger anisotropy in the sediments or the addition of transient effects, such as a decreasing sedimentation rate in time, will increase upward flow.

[15] Pore fluid focusing creates elevated excess pore pressures at the ridge axis, promoting the formation of high-angle fractures within the sediments [Bruno, 1994]. For example, Weinberger and Brown [2006] conclude that near-vertical fractures found near the crest at Hydrate Ridge (Oregon, USA) were most likely formed due to the extensional stress regime of the ridge undergoing gravitational collapse. Once fractures form, they are an efficient mechanism to carry dissolved methane (or free gas [Flemings et al., 2003]) upward into the hydrate stability zone from below. Highly localized methane hydrate deposits associated with near-vertical faults and fractures have been found at Blake Ridge [Paull et al., 2000]. Such large deposits are often attributed to strong upward methane-bearing fluid advection along the fractured regions.

Magnitudes of upward fluid flux predicted by our model through a small fractured zone are within the range of fluid fluxes required at the base of the hydrate stability zone to form hydrate by Xu and Ruppel [1999], namely 0.3–2.0 mm yr\(^{-1}\). For example, our model predicts an upward fluid flux of 0.26 mm yr\(^{-1}\) and 1.3 mm yr\(^{-1}\) at 500 mbsf when 15% and 2.5% of the seafloor area is fractured, respectively (results shown in auxiliary material). More recently, high angle dendritic conduits have been mapped within the Blake Ridge gas hydrate province by Hornbach et al. [2007], showing a distribution of distinct permeable zones within the sediments.

[16] A one-dimensional model of sedimentation and compaction implies downward pore fluid migration through the hydrate stability zone, whereas many models of hydrate formation require upward transport of methane-bearing pore fluid from below. We show that upward flow relative to the seafloor is feasible in marine sediments with anisotropic permeability beneath regions of topography and through high-angle fractures. Fracture formation may be aided by high excess pore pressures when topography permits preferential flow along sloping bedding planes.

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### References


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Supplementary Section

To accompany: *Topography- and fracture-driven fluid focusing in layered ocean sediments*
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0.1 Sediment Permeability

A Kozeny-Carman relation [1] is used to describe the vertical sediment permeability given a porosity profile $\phi(z)$ described by Athy’s Law. The sediment permeability used in our model is a modified form of the Kozeny-Carman relationship which includes a percolation porosity $\phi_c$. The percolation porosity was first introduced by Mavko & Nur (1997), and is the fraction of porosity which is disconnected and does not contribute to flow through a porous media. The value of $\phi_c$ typically ranges from 0 to 0.05. Figure 1B shows the modified form of the Kozeny-Carman relationship used and the resulting sediment permeability profile with depth. $K_o$ and $\phi_o$ are the sediment permeability and porosity at the seafloor, respectively.

0.2 Fluid Flux Rates Through Fractured Zone

Magnitudes of upward fluid flux predicted by our model through a small fractured zone are within the range of fluid fluxes required at the base of the hydrate stability zone to form hydrate by Xu & Ruppel (1999), namely 0.3-2.0 mm yr$^{-1}$. For example, our model predicts an upward fluid flux of 0.26 mm yr$^{-1}$ and 1.3 mm yr$^{-1}$ at 500 mbsf (representative of the bottom of the hydrate stability zone at Blake Ridge [3]) when 15% and 2.5% of the seafloor area is fractured, respectively (see Figure 1A).

Figure 1: A. Averaged fluid fluxes relative to the seafloor through fractured zones which span a range of the percentage of the seafloor area. Fractured zones extend 1km into the sediment column. Fractured zones occupying smaller percentages of seafloor area produce larger upward fluid flux. B. Sediment permeability as given by a modified form of the Kozeny-Carman relation.
Bibliography


