Direct pore-level observation of permeability increase in two-phase flow by shaking

Igor Beresnev,[1] William Gaul,[2] and R. Dennis Vigil[2]

[1] Increases in permeability of natural reservoirs and aquifers by passing seismic waves have been well documented. If the physical causes of this phenomenon can be understood, technological applications would be possible for controlling the flow in hydrologic systems or enhancing production from oil reservoirs. The explanation of the dynamically increased mobility of underground fluids must lie at the pore level. The natural fluids can be viewed as two-phase systems, composed of water as the wetting phase and of dispersed non-wetting globules of gas or organic fluids, flowing through tortuous constricted channels. Capillary forces prevent free motion of the suspended non-wetting droplets, which tend to become immobilized in capillary constrictions. The capillary entrapment significantly reduces macroscopic permeability. In a controlled experiment with a constricted capillary channel, we immobilize the suspended ganglia and test the model of capillary entrapment: it agrees precisely with the experiment. We then demonstrate by direct optical pore-level observation that the vibrations applied to the wall of the channel liberate the trapped ganglia if a predictable critical acceleration is reached. When the droplet begins to progressively advance, the permeability is restored. The mobilizing acceleration in the elastic wave, needed to "unplug" an immobile flow, is theoretically calculated within a factor of 1–5 of the experimental value. Overcoming the capillary entrapment in porous channels is hypothesized to be one of the principal pore-scale mechanisms by which natural permeabilities are enhanced by the passage of elastic waves. **Citation:** Beresnev, I., W. Gaul, and R. D. Vigil (2011), Direct pore-level observation of permeability increase in two-phase flow by shaking, *Geophys. Res. Lett.*, *38*, L20302, doi:10.1029/2011GL048840.

1. Introduction

[2] Permeability increases in porous geologic formations induced by the passage of seismic waves, e.g., at the times of earthquakes, have been well documented. In nature, they may lead to a greater inflow of groundwater into aquifers or enhanced productivity of oil wells [*Beresnev and Johnson*, 1994; *Roberts*, 2005; *Elkhoury et al.*, 2006]. Despite sufficient evidence of the widespread nature of the phenomenon, its underlying physical mechanism has remained unclear. Understanding this mechanism could help harness the phenomenon and turn it into a technology of controlled permeability, with far-reaching practical implications in hydrology and reservoir engineering [*Roberts et al.*, 2003; *Elkhoury et al.*, 2006]. Direct observation of the enhanced fluid flow under the effect of elastic waves at the pore level could be a way of revealing such an underlying pore-scale mechanism.

[3] A feature that most aquifers and petroleum reservoirs share is their being two-phase hydrological systems, in which one phase is wetting and one is non-wetting. The non-wetting phase forms isolated droplets, surrounded by the suspending wetting fluid, usually water. In petroleum reservoirs, the non-wetting phase is oil, existing in the form of isolated droplets (ganglia), and in aquifers it is composed of air bubbles. Realistic pore channels also are tortuous, formed by a succession of open spaces connected by narrow constrictions (pore throats). The flow of dispersed non-wetting globules of oil and air through the constrictions is resisted by capillary forces: if the pressure gradient driving the flow is sufficiently low, entrapment of the globules in pore constrictions takes place. This capillary entrapment is known as the Jamin effect [*Taber*, 1969]. The Jamin effect, restricting the two-phase flow through channels of variable cross-section, explains, for example, the danger of introducing air bubbles into the blood stream. A natural porous system contains many channels with widely varying tortuous geometries. The entrapped non-wetting droplets "plug" the flow in some of them, while in others the flow may still be occurring. When the effect is summed up over a multitude of channels, the macroscopic permeability of the porous volume is significantly reduced.

[4] One of the mechanisms of reduced permeability in two-phase hydrological systems thus has capillary nature. If the local vibrations, induced by the passage of seismic waves, can mobilize the entrapped globules that plug the flow, the flow rate through the volume will increase, which will be seen as increased macroscopic permeability. This is a possible explanation of the enhancing effect of seismic waves on the permeability in reservoirs and aquifers.

[5] We built an experimental apparatus that allows us to entrap a ganglion of a non-wetting fluid, suspended in a wetting phase, in a transparent constricted capillary. The capillary is subjected to longitudinal vibrations, which correspond to the oscillations induced on the wall of a natural pore by a passing wave, resolved onto the pore axis. We present the demonstration of the mobilization of an initially immobile ganglion with the beginning of vibrations and address the quantitative explanation of the phenomenon.

2. Experiment Description

[6] An axisymmetric sinusoidally-constricted capillary was manufactured from commercial glass tubing by a glassblower. The tube minimum ($r_{\min}$) and maximum ($r_{\max}$)

[1]Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa, USA.
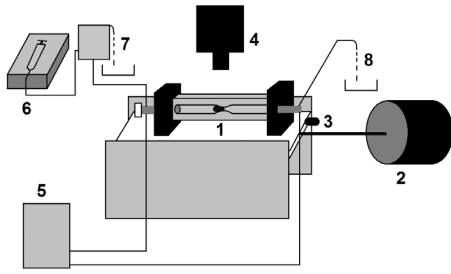[2]Department of Chemical and Biological Engineering, Iowa State University, Ames, Iowa, USA.

Figure 1. Schematics of the experiment demonstrating the mobilizing effect of longitudinal vibrations on the immiscible two-phase flow in channels with uneven profile. 1. Constricted capillary; 2. Shaker; 3. Accelerometer; 4. Camera; 5. Manometer/pressure-transducer; 6. Syringe pump; 7. Overflow feed tank; 8. Outflow.

radii are 0.12 and 4.23 mm, and the wavelength is 24.2 mm. The capillary was placed inside a transparent Lucite viewing box. The region between the viewing cell and the tube was filled with a glycerol solution matched to the refractive index of the glass tube (Figure 1). Small ports at either end of the viewing cell provided access for feeding and removing the working fluids into or out of the capillary. At the inlet side there are two ports: one for the suspending fluid and one, covered with a rubber septum, for the injection of the core (non-wetting) fluid. Images of the tube were captured by a high-speed digital camera with a magnifying lens mounted above the flow cell.

[7] Deionized water was used as the suspending fluid (viscosity of 10^{-3} Pa s). The core organic phase was a trichloroethylene-heptane mixture dyed with Oil Blue N (viscosity of 0.44×10^{-3} Pa s). The densities ρ of the two phases were matched to 998 kg/m^3 to eliminate buoyancy effects. The fluid-fluid interfacial tension σ was 16×10^{-3} N/m.

[8] To remove any residue and increase the hydrophilicity of the glass, the capillary was first cleaned in a NaOH-ethanol-deionized-water solution and then flushed with deionized water and dried. In a given run, the capillary was first filled with the suspending fluid, and a known volume of the core phase sufficient to fill the constriction was injected upstream of the constriction via a syringe. Flow was controlled by a gravity feed system. A syringe pump constantly fills an overflow feed tank whose height can be adjusted precisely with a micrometer stage while the outflow tube is kept at a fixed height: this creates a constant external pressure drop ΔP_e along the capillary, driving the flow. The pressure drop was measured with an inclined manometer and a differential pressure transducer.

[9] As a suspended droplet of the core fluid moves toward the channel's constriction, and if ΔP_e is below a certain critical value (the "static" threshold ΔP_{th}), the droplet is unable to overcome the capillary barrier and is trapped. The flow is "plugged" and the permeability is effectively zero. The mobilization threshold can be experimentally determined by first keeping $\Delta P_e < \Delta P_{th}$, entrapping the drop, and then slowly raising the feed tank until the droplet movement through the constriction takes place. The flow is "unplugged" and the permeability is restored. The mobilizing pressure drop is then ΔP_{th}.

[10] For the experiment with vibrations, the background pressure drop ΔP_e is established below ΔP_{th}, to first entrap

the ganglion. The shaker then starts to sinusoidally vibrate the capillary-tube assembly in the axial direction at a given frequency. The vibration starts at a low amplitude and is increased in a stepwise manner, lasting several tens of vibration periods at each step to wait for the mobilization. The amplitude A of the longitudinal acceleration of the tube is measured by an accelerometer. If an amplitude can be reached at which the ganglion starts to progressively advance and exits the constriction, it is referred to as the threshold acceleration amplitude A_{th}. The flow is unplugged and permeability is restored solely by the application of vibrations.

3. Demonstration of the Mobilization of Plugged Flow by Vibrations

[11] As discussed by *Beresnev* [2006] and *Beresnev and Deng* [2010], the value of the mobilizing acceleration can significantly increase with the frequency. Higher-frequency waves also attenuate in rock much faster, which makes them less practically relevant. For these reasons, the experiments were run at the vibration frequencies of 5, 7.4, 10, and 14.2 Hz in the "seismic" range. The frequencies are increased by $\sqrt{2}$, with minor deviations for purely technical reasons. At each frequency, runs were made with one to three different values of the background pressure drop ΔP_e, as summarized in Table 1. The experimentally determined static thresholds ΔP_{th} and the lengths l of the entrapped ganglia, measured between the front and rear three-phase contact lines, are also indicated.

[12] If the model of capillary entrapment holds, the static threshold can be determined via

$$\Delta P_{th} = 2\sigma(1/r_{\min} - 1/r_r), \qquad (1)$$

where r_r is the radius of the rear meniscus, assuming the spherical menisci shapes [*Taber*, 1969; *Beresnev*, 2006]. The experimentally determined values of ΔP_{th} from Table 1 are compared with those calculated from equation (1), for the different lengths of the entrapped ganglion l, in Figure 2. The agreement is excellent.

[13] In all cases but one (5 Hz, $\Delta P_e = 95$ Pa) (Table 1), an entrapped ganglion, resting under the external pressure drop ΔP_e with the front meniscus inside the constriction and unable to move, became mobilized (and the flow unplugged) when a vibration of sufficiently large amplitude was applied. The threshold acceleration amplitudes A_{th} are also shown in Table 1. Figure 3 presents, as an example, a magnified camera view (from above) of the movement of the initially entrapped droplet (dark color at right) through the constriction, displacing the water ahead (light color at left), for the $\Delta P_e = 171$ Pa, 5 Hz case. The position of the front meniscus is indicated by the arrows. Small air bubbles are also seen in the water. The time stamps are from the start

Table 1. Experimental Values of Frequencies, Pressure Drops, and Ganglion Lengths

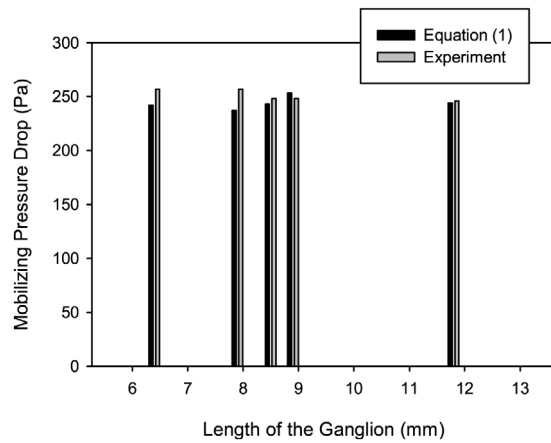|	5 Hz	5 Hz	5 Hz	7.4 Hz	7.4 Hz	10 Hz	14.2 Hz
ΔP_e (Pa)	95	171	227	206	237	203	183
ΔP_{th} (Pa)	246	246	246	257	248	248	257
l (mm)	11.8	11.8	11.8	6.4	8.9	8.5	7.9
A_{th} (m/s^2)	–	0.9	0.7	1.6	0.6	1.3	3.2

Figure 2. Comparison of the static mobilization thresholds ΔP_{th}, determined from the model of capillary entrapment (equation (1)), with the experimentally measured values.

of the vibrations. The images are separated by exactly two periods of vibration. It should be noted, though, that Figure 3 is provided for a rough illustration of the process only. Since the mobilization takes many periods to be complete, it is impossible to render its rich dynamic process in a few reduced-size still images. Therefore, a complete animation is provided as Animation S1 in the auxiliary material, which the reader needs to watch before continuing.[1]

[14] The movie starts with an entrapped ganglion at rest. The time when the vibrations began is marked as zero. The starting amplitude of the vibrations is 0.06 g (0.6 m/s^2) (g is the acceleration of gravity). It increases to 0.08 g (0.8 m/s^2) at approximately 5.3 s, and to 0.09 g (0.9 m/s^2) at 14.9 s. As one can see, the two initial amplitudes are insufficiently strong to mobilize the droplet, which simply continued back-and-forth movements within the constriction. However, when the threshold value of 0.9 m/s^2 was attained, the droplet became fully mobile in approximately eleven periods, resuming its unrestricted flow through the capillary. The capillary barrier was overcome.

4. Explanation of the Observations

[15] Is it possible to quantitatively explain the existence and variability of the threshold acceleration needed to "unplug" an immobile two-phase flow system? A "static" mobilization criterion and a dynamic theory of the mobilization of entrapped blobs of non-wetting fluids have been proposed by *Beresnev* [2006] and *Beresnev and Deng* [2010]. In the immobile state, the background pressure drop along the blob is resisted by capillary force. The application of vibrations creates an extra "inertial" forcing that adds to the background pressure gradient. When the sum of the background and the vibrational inertial forcing exceeds the resisting capillary force, the mobilization takes place. The relationship between these three body forces at the liberation moment leads to the mobilization criterion for the threshold acceleration amplitude [*Beresnev*, 2006],

$$A_{th} = (\Delta P_{th} - \Delta P_e)/\rho l. \qquad (2)$$

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048840.
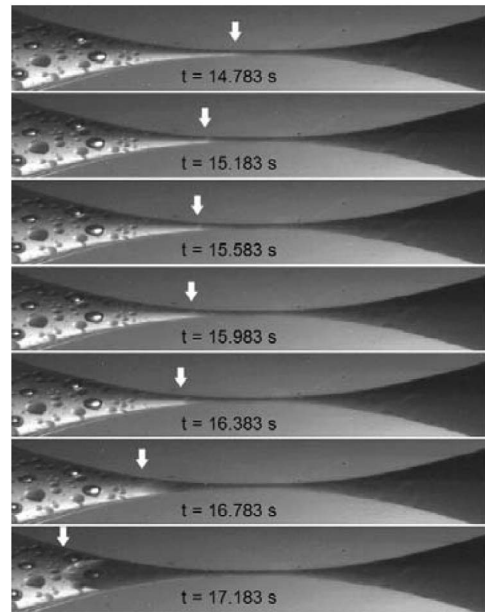

Figure 3. Snapshots from Animation S1 showing the liberation of an entrapped non-wetting ganglion under the effect of vibrations.

On the other hand, the balance of all body forces acting on the ganglion, including the external gradient, the capillary force, the oscillatory forcing created by vibrations, and the viscous drag, can be combined in a single equation of motion, leading to a dynamic theory of the phenomenon [*Beresnev*, 2006; *Beresnev and Deng*, 2010].

[16] Equation (2) shows that the inertial body force ρA_{th} has to be added by vibrations to compensate for the "resisting" body force $(\Delta P_{th} - \Delta P_e)/l$. This can be thought of as an additional external pressure gradient instantly added to the system.

[17] Figure 4 shows the comparison of the mobilizing accelerations predicted by both the mobilization criterion
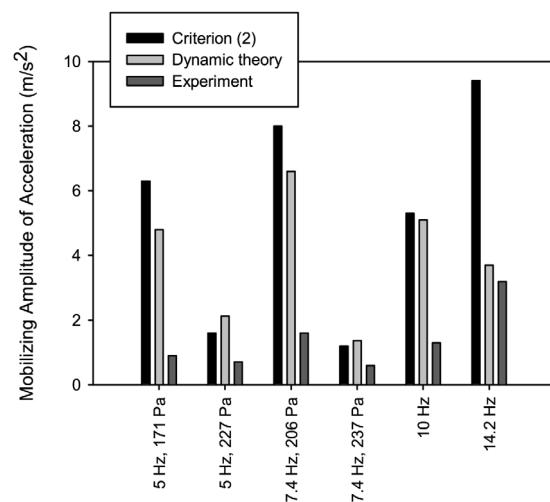

Figure 4. Comparison of the threshold amplitude A_{th} of acceleration required to unplug an entrapped blob: mobilization criterion (2), dynamic theory, and experiment.

(2) and the dynamic theory, relative to the experimental values. To obtain the theoretical values, equation (8) of *Beresnev* [2006], with the viscous term, introduced by *Beresnev and Deng* [2010, equation 6], added was numerically solved. Comparisons are presented for all combinations of experimental parameters in Table 1. The dynamic theory is generally closer, expectedly, to the experimental values than a simpler static criterion, predicting the mobilizing acceleration almost exactly for the case of 14.2 Hz. Overall, the theory consistently overpredicts the observed acceleration by a factor of 1.2 to 5.3. The deviations from the experiment can be due to a number of factors, including the dynamic contact angle, the non-ideal spherical shape of the menisci, and the non-ideal sinusoidal shape of the constriction. Since there is not a satisfactory analytical model for a dynamic contact angle and the shape of a moving meniscus, a theory providing a more accurate match to the observations seems unfeasible at present.

[18] The value of A_{th} is generally dependent on both the magnitude of the "capillary barrier" $(\Delta P_{th} - \Delta P_e)$ and the frequency of vibrations [*Beresnev*, 2006; *Beresnev and Deng*, 2010]. The mobilization criterion (2) only captures the dependence on $(\Delta P_{th} - \Delta P_e)$ (from which its name "static" is derived), while the full dynamic theory is needed to capture both effects. This is one of the explanations why the values calculated from the theory in Figure 4 are generally in better agreement with the experiment.

[19] *Beresnev* [2006, equations 9–10] also proposed that the frequency of the vibratory action be low enough for the stimulation to be effective, to allow the fluids sufficient time to respond. This threshold frequency is estimated as the inverse of the viscous response time τ, $\tau = \rho r^2/\mu$, where r is the channel radius and μ is the fluid viscosity. For the meniscus in the constriction, with the values of the order $\rho = 10^3$ kg/m^3, $r = 0.1$ mm, $\mu = 10^{-3}$ Pa s, the threshold frequency is $1/\tau = 100$ Hz. The frequencies used in the experiments are thus below the estimated threshold.

[20] The theoretical framework available also offers an explanation of the only case (5 Hz, $\Delta P_e = 95$ Pa) when the mobilization of the entrapped droplet was not attained. The technical limit on the maximum acceleration amplitude of the shaker is 0.45 g (4.4 m/s^2); the application of this acceleration did not lead to the mobilization. The threshold amplitudes A_{th} calculated from equation (2) and the dynamic theory are 12.6 and 4.7 m/s^2, respectively. These values are consistent with the observation: the experimentally applied acceleration was still below (if only slightly) the theoretical unplugging level.

5. Conclusions

[21] Increases in permeability of natural hydrological and reservoir systems induced by passing seismic waves have been reliably documented. A quantitative explanation of the phenomenon, based on a testable physical mechanism, has nevertheless been missing. Understanding the pore-scale mechanism of the permeability enhancement is a pre-requisite for possible uses of this phenomenon to achieve controlled or engineered permeability, with potentially significant economic implications.

[22] Natural reservoirs and aquifers typically are two-phase fluid systems, filled with water as a wetting phase that suspends the non-wetting globules, such as gas or organic fluids. Capillary forces restrict the free movement of the suspended phase through the tortuous porous channels, entrapping the non-wetting globules in the narrow pore throats. The permeability of a channel with an entrapped droplet is effectively reduced to zero.

[23] An entrapped body can be mobilized if an external pressure drop along its length exceeds a certain critical value. We compared these threshold values determined from the model of capillary entrapment with the experimentally observed ones: the agreement is excellent.

[24] We have further experimentally demonstrated that the capillary entrapment is overcome if longitudinal vibrations of a critical amplitude are applied to the wall of the channel, "unplugging" the stuck body and restoring the permeability. The "unplugging" effect of vibrations on two-phase flow should be one of the pore-scale mechanisms by which seismic waves enhance permeability of the natural fluid-saturated porous systems. Other possible mechanisms may exist at the intermediate levels between the pore and the field scales. One of the effects under investigation in fractured laboratory samples is unclogging of fracture apertures by the mobilization of fine particles, induced by shaking or pulsing pressure [*Liu and Manga*, 2009; *Elkhoury et al.*, 2011].

[25] An analytical model of the droplet mobilization by seismic waves adequately explains the observations. It is able to predict the amplitude of the mobilizing acceleration within a factor of 1–5 of the observed value. Given the uncertainties in parameterizing the dynamic contact angle and the shape of a moving meniscus, a better theory of the seismic permeability enhancement seems to be beyond reach at present time.

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I. Beresnev, Department of Geological and Atmospheric Sciences, Iowa State University, 253 Science I, Ames, IA 50011-3212, USA. (beresnev@iastate.edu)

W. Gaul and R. D. Vigil, Department of Chemical and Biological Engineering, Iowa State University, 2114 Sweeney Hall, Ames, IA 50011-2230, USA.