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LABORATORY OBSERVATIONS OF ALTERED POROUS FLUID-FLOW BEHAVIOR IN BEREA SANDSTONE INDUCED BY LOW-FREQUENCY DYNAMIC STRESS STIMULATION

© 2005 г. Peter M. Roberts

Los Alamos National Laboratory Earth and Environmental Sciences Division

EES-11, Mail Stop D443 Los Alamos, NM 87545

USAPhone: +01-505-667-1199

Email: proberts@lanl.gov

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It has been observed repeatedly that low-frequency (1 to 500 Hz) seismic stress waves can enhance oil production from depleted reservoirs and contaminant extraction from groundwater aquifers. The physics coupling stress waves to fluid flow behavior in porous media is not understood, although numerous physical mechanisms have been proposed to explain the observations. To quantify the effects of low-frequency, dynamic-stress stimulation on multiphase fluid flow and in-situ particle behavior in porous media, laboratory experiments were conducted with a core-flow stimulation apparatus that allows precise control and measurement of applied stress/strain, static confinement and fluid-flow parameters. Results are reported for experiments on stimulated single-phase and 2-phase fluid-flow behavior in 2.54-cm-diameter Berea sandstone cores. For all experiments, stimulation was applied to the cores in the form of sinusoidal, axial, mechanical stress coupled to the solid porous matrix at frequencies of 25 to 75 Hz. Applied stress RMS amplitudes ranged from 300 to 1200 kPa and, at these levels, produced coupled, pore-pressure fluctuations much less than 1.2 to 4.8 kPa, respectively. During single-phase brine flow, stimulation increased the absolute permeability of the rock by 10 to 20 percent. This was caused by mobilizing in-situ clay particles that were partially plugging the pore throats. During 2-phase, steady-state, constant-rate flow of oil-plus-brine and decane-plus-brine mixtures, stimulation caused significant changes in the bulk fluid pressure drop across the core. The pressure changes showed a strong dependence on the viscosity of the non-wetting fluid phase (oil or decane) relative to the wetting phase (brine). This may indicate that relative changes in the mobility of wetting versus non-wetting fluid phases were induced by the dynamic stress. Under the specific experimental conditions used, pore-scale particle perturbation and altered wettability are possible physical mechanisms that can explain the results.

INTRODUCTION

Numerous investigations have shown that seismic waves (low-amplitude stress waves at frequencies of 1 to 500 Hz) can selectively increase the mobility and transport of multi-phase fluid components in porous media such as rocks and soils [1, 2, 3, 4, 5]. Most of the prior and ongoing research in this area has been focused on increasing production from declining oil and gas reservoirs during field deployments of various surface and downhole seismic sources. During several field tests by the oil and gas industry [1, 2, 5], increases in oil production rates by 20% or more have been reported. However, the majority of oil-field tests to date have been performed with little or no guidance from laboratory experimental data or theoretical predictions. Thus, field tests have yielded mixed and unpredictable results, mainly because the underlying physical mechanisms for seismically enhanced fluid transport are not adequately understood.

More recently, research has also begun to examine the possibility of using seismic wave stimulation to enhance the extraction of dense non-aqueous-phase liquid (DNAPL) contaminants from groundwater aquifers. In contrast to the numerous field tests already performed on stimulated flow of oil, which is a light non-aqueous-phase liquid (LNAPL), no field tests have been performed yet on enhancing DNAPL extraction at groundwater remediation sites in the U.S. Furthermore, only a limited number of laboratory experiments have been performed on enhanced DNAPL transport in unconsolidated sands or soils [6, 7]. The obvious practical value of harnessing the stress-stimulated flow phenomenon has, over the past ten years, motivated increased research interest in the subject. Despite this growth, the scientific community is far from fully understanding the phenomenon.

Recent laboratory experiments on stimulated 2-phase fluid flow in rocks and sands [6, 7, 8, 9] and theoretical studies on coupled stress/fluid-flow dynamics [10, 11, 12, 13, 14, 15] have confirmed that the stress-stimulation phenomenon is observable at the bench scale, reproducible, and can be modeled. However, lab experiments have produced mostly empirical data, and theoretical models are still in the initial stages of

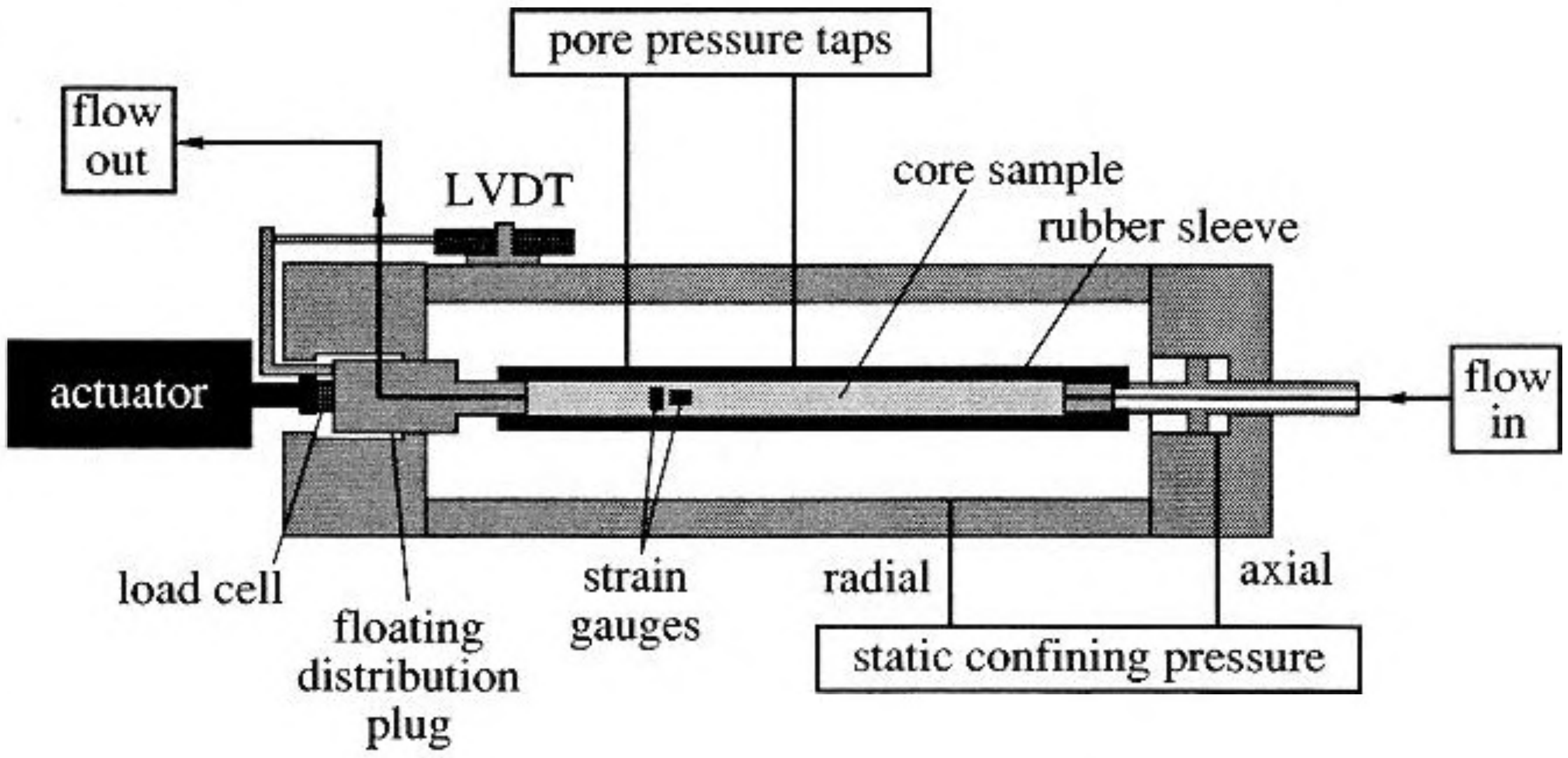

Fig. 1. Schematic diagram of dynamic-stress, core-flow stimulation apparatus.

development. Numerous physical mechanisms have been proposed to explain seismically enhanced NAPL mobilization, but no conclusive experimental laboratory or field data have been collected that can prove which mechanisms dominate under the widely varying physical conditions typically encountered in the Earth.

Although "stress-wave propagation in saturated porous media" and "multi-phase porous fluid flow dynamics" are each well-developed individual scientific fields, they have not yet been cross-coupled successfully. Initial theoretical work indicates that cross-coupling of stress waves with fluid flow can be modeled using simplified physical conditions [10, 13, 15]. Under more realistic conditions in the Earth, the coupling is likely controlled by a combination of several different mechanisms, each operating over a different range of scale lengths. The stress-wave stimulated porous flow phenomenon, then, needs to be understood from the subpore scale (nm to μm) to the field scale (m to km). This would allow prediction of the stimulated flow response for different combinations of physical conditions and applied dynamic stress parameters.

This paper reports recent laboratory experimental results on core samples of Berea sandstone that provide further evidence that low-frequency stress stimulation can alter porous fluid flow behavior. The data were obtained with a high degree of accuracy and precision, and demonstrate that the phenomenon is readily induced and can be quantified. The observed core-scale (cm) behavior supports two physical mechanisms that are likely to be important for understanding how to predict and control the stress-stimulated flow phenomenon at larger scales as well. These are 1) in-situ clay particle mobilization and 2) pore fluid wettability alteration. Because the results are still largely empirical, no proof can be presented yet that other physical mechanisms are not also partially contributing to the observations.

LABORATORY APPARATUS

To investigate the effects of low-frequency stress stimulation on porous fluid-flow behavior in the laboratory, a specialized core flow apparatus was constructed (Figure 1). This apparatus is part of a unique, state-of-the-art facility designed specifically for this purpose. The main component of the system is a triaxial core holder capable of applying up to 70 MPa axial and radial confining pressure to a cylindrical core sample. The sample is placed inside a horizontal Viton rubber sleeve designed to hold cores 2.54 cm in diameter and up to 60 cm long. Distribution plugs at each end of the sleeve accommodate fluid flow through the core. Radial confining pressure is applied to the main hydraulic-fluid chamber surrounding the sleeve. Static axial confinement is applied separately by a hydraulic piston attached to the inlet distribution plug (at the right end in Fig. 1).

The apparatus was designed to study a wide range of physical conditions under which stress stimulation may prove to be a useful application. Specifically, the pressure ratings are appropriate for simulating in-situ overburden and pore-pressure conditions at crustal depths up to approximately 3 km. During the experiments, constant-flow-rate pumps are used to produce pulse-free flow of fluids through the core at flow rates ranging from 0.02 to 200 mL/min. A back-pressure regulator at the fluid outlet end of the apparatus provides precise control over the static pore pressure during flow. The permeability along the core sample is measured using differential pressure gauges connected by tubing to taps located every 5 cm along the length of the rubber confining sleeve. The measured pressure drop across the core is converted to permeability using Darcy's law [16].

To dynamically stimulate the core samples, axial stress cycling at frequencies from 1 to 500 Hz is produced by direct mechanical coupling of the core sample to a Terfenol-D magneto-strictive actuator. The actuator can deliver dynamic force as high as 900 N peak amplitude with a maximum displacement of 70 mi-

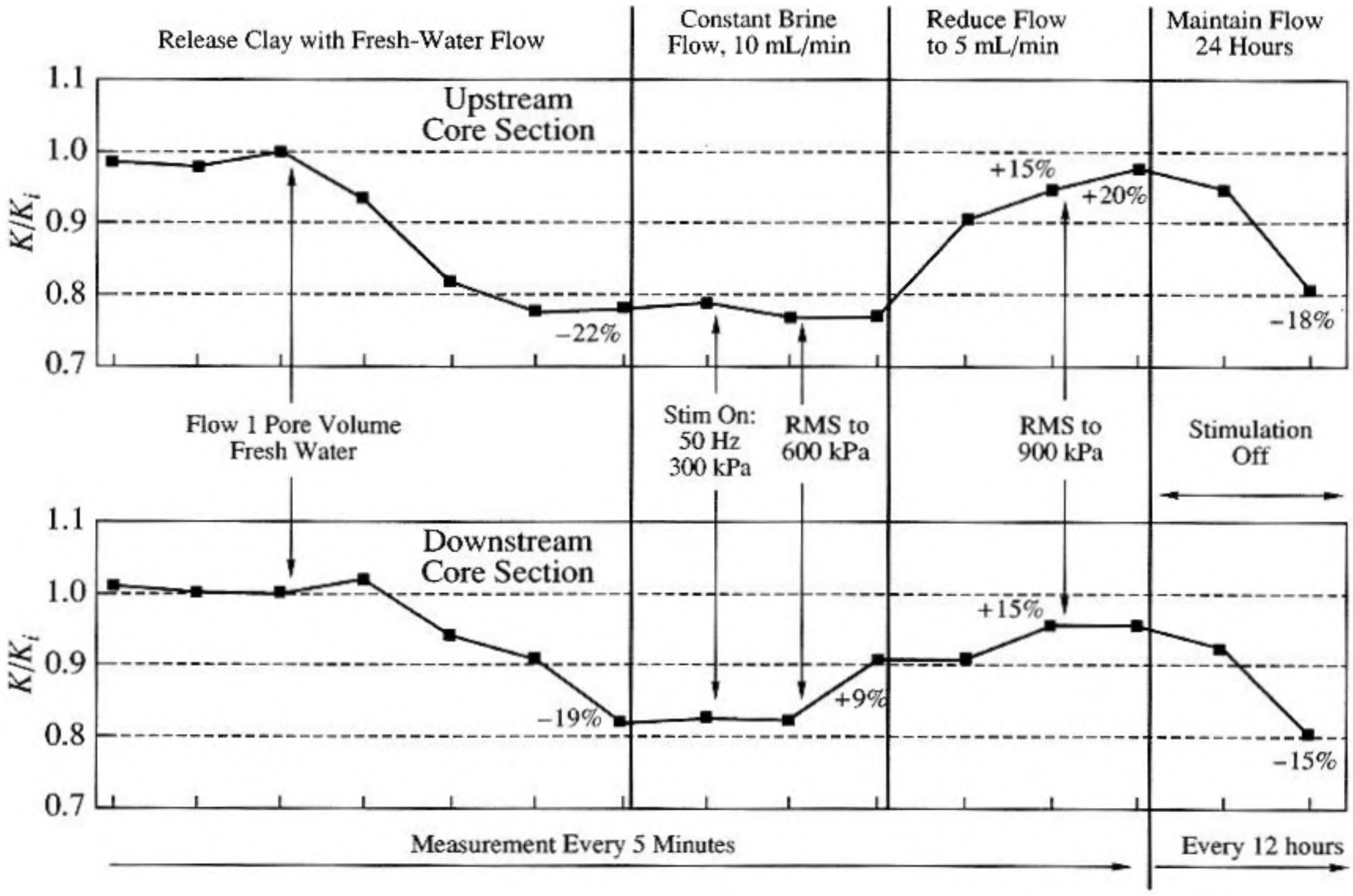

Fig. 2. Permeability changes during single-phase brine flow caused by release of in-situ clay fines and subsequent mobilization by low-frequency stress stimulation.

crons, producing axial strains as high as 10^{-4}. A load cell in series with the actuator, an LVDT attached to the floating distribution plug, and strain gauges attached to the core provide calibrated stress and strain data during stimulation. The fluid-pressure gauges are also used to estimate dynamic pore-pressure fluctuations induced by the stimulation.

Another mode of stimulation that has been investigated by other researchers [7, 8] is to vibrate porous samples during flow using shaker tables. The apparatus used here (Fig. 1) has been designed to minimize this type of excitation because it causes translational, non-strain energy that does not typically occur at significant depth in the Earth when a seismic wave propagates through it. To maximize the mechanical stress component of the dynamic stimulation and minimize the vibrational component, the axial load piston at the inlet (right) end of the core holder is locked in place mechanically after the desired static axial confinement is applied. This immobilizes the inlet end of the core and the particle acceleration induced by the actuator effectively vanishes there. Thus, wave propagation does not occur during stress stimulation because the core is simply being compressed and expanded like a spring. This, in turn, partly avoids wavelength scaling issues when comparing laboratory and field results.

EXPERIMENTAL RESULTS

Single-Phase Flow Experiments

Experiments were performed to investigate a physical mechanism proposed for increasing absolute permeability: mobilization of in-situ clay particles by stress stimulation. This mechanism has previously been demonstrated as feasible using ultrasonic energy at 10 kHz and above [17, 18, 19], but had not been observed at seismic frequencies of 100 Hz and lower. A Berea sandstone core sample, 2.54 cm in diameter and 32 cm long, with initial permeability of approximately 800 millidarcies (md) was confined at 7 MPa static radial and 5.5 MPa static axial pressures. Constant flow of a 3%-by-weight brine solution was then initiated at a rate of 10 mL/minute. Brine was used to stabilize in-situ clay particles (fines) during permeability measurements. At lower salinity, clay fines that are normally attached to the pore walls will release and plug the pore throats during flow, thus decreasing the rock's permeability. The permeability measurements for this experiment are plotted in Figure 2 for two separate 5-cm long sections of the core sample. The top plot is for an "upstream" section closest to the fluid inlet and the bottom plot is for a "downstream" section closest to the fluid outlet and the stimulation source. The measured permeability, K, is normalized by the baseline permeability, Ki, obtained during initial brine flow.

To induce a controlled release of clay particles, one pore volume of fresh water was flowed through the core. This resulted in a decrease in absolute permeability of approximately 20% across the entire core. The upstream section was affected sooner than the downstream section because of the flow direction. After returning to 3%-brine flow and establishing a new stabile permeability, continuous, sinusoidal stress cycling was initiated at 50 Hz and 300 kPa RMS stress amplitude. No change in permeability was observed in either core section until the stress amplitude was increased to 600 kPa RMS, after which an increase of 9% was observed in the downstream core section. No change was observed in the upstream core section until the brine flow rate was dropped from 10 ml/min to 5 ml/min. At the lower flow rate, the upstream permeability rose by 15%, and the downstream permeability increased an additional 6% to a final value of 15%. This means that the ability to mobilize clay particles that are plugging pore throats is sensitive to the absolute pore pressure and/or the fluid pressure gradient in the rock as a function of length along the core. When the RMS stimulation amplitude was increased to 900 kPa, an additional 5% permeability increase was observed in the upstream core section but not in the downstream section. After turning off the stimulation and maintaining constant brine flow, the permeability of the entire core gradually dropped back to the pre-stimulation values over a period of 24 hours. This occurred because stimulation was not applied long enough to expel the mobilized clay particles, and they subsequently re-plugged the pore throats during continued flow.

Two-Phase Steady-State Flow Experiments

Experiments were performed to investigate dynamic stress effects on steady-state, 2-phase immiscible fluid flow through Berea sandstone. The cores used were again 2.54 cm in diameter and 32 cm long, but had an initial intrinsic permeability of 100 md. The samples were confined at 7 MPa radial pressure and 4 MPa axial pressure. Two constant-rate fluid pumps were used to flow both immiscible phases through the core simultaneously at different flow-rate ratios. For the first experiment, decane was used as the non-wetting fluid phase and brine as the wetting phase. The second experiment used 10-weight vacuum pump oil as the non-wetting phase instead of decane. The reason for this was to determine if the viscosity of the non-wetting phase has an effect on 2-phase flow behavior induced during dynamic stress stimulation. Decane was chosen because it has a viscosity (approximately 0.9 cP) lower than water (1.0 cP), and 10-weight oil because it's viscosity (approximately 90 cP) is higher than that of water. A different 100-md Berea core sample was used for each experiment.

During 2-phase flow, the total bulk fluid flow rate was held constant, but the ratio of decane (or oil) to brine flow rates was varied to investigate the dependence of the stimulated flow behavior on water saturation. For the decane-plus-brine experiment the bulk flow rate used was 2.0 mL/minute. To achieve similar pressure drops for the oil-plus-brine experiment, the bulk flow rate was dropped to 0.5 mL/minute. The procedure for both experiments was to start the two fluids flowing at a given flow-rate ratio, and wait until the bulk-fluid pressure drop across the entire core stabilized at a constant value, indicating that steady-state conditions were achieved. Then, sinusoidal, mechanical stimulation was applied as before, and induced changes in the bulk-fluid pressure drop were recorded. Stimulation frequencies and RMS stress amplitudes were varied during the decane-plus-brine experiment while holding the flow-rate ratio constant. During the oil-plus-brine experiment, however, the same frequency and RMS amplitude were used throughout.

The results for the decane-plus-brine experiments are shown in Figure 3. Bulk-fluid pressure drops are plotted versus flow time for the entire 32-cm core length (top plot), and for a 5-cm-long section in the middle of the core (bottom plot). The left half of each plot shows results when the decane fractional flow rate was 25% of the combined bulk flow rate of 2.0 mL/min, and the right half shows results for 10% decane flow. Stress stimulation treatments are indicated by the arrows, and the frequency and RMS amplitudes used are labeled.

In general, stress stimulation caused the bulk fluid pressure drop across the core to decrease. During 25% decane flow, the pressure drops behaved erratically, but there is a correlation between applied stress and sudden decreases in pressure. During 10% decane flow, the correlation is much clearer and the magnitude of the pressure change increases with applied RMS stress amplitude. Also, when stimulation is turned off, the pressure drops return rapidly toward pre-stimulation values. This behavior was not observed during flow runs (not shown) where the decane fractional flow rate was 50% or less. Figure 3 shows results only for stimulation at 50 Hz. Additional runs (not shown) for 10% decane flow were performed where the stimulation frequency was varied from 25 Hz to 75 Hz while holding the stress amplitude constant. The largest decrease in bulk-fluid pressure drop was observed at 25 Hz and the smallest at 75 Hz. Thus, lower frequencies were most effective at inducing the observed pressure changes.

The results for the oil-plus-brine experiment are shown in Figure 4. Bulk-fluid pressure drops across the entire 32-cm core length are plotted for four different oil fractional flow rates (10, 30, 50 and 70% of the combined bulk flow rate of 0.5 mL/min), indicated above each plot. The plots are shifted to line up at the times when stress stimulation was applied at 25 Hz and 1000 kPa RMS stress amplitude. In contrast to the decane-plus-brine behavior (see Figure 3), stimulation caused the pressure drop across the core to increase when flowing oil-plus-brine, and this behavior was observed for all fractional oil flow rates. At each flow-rate ratio, stimulation was applied continuously and turned

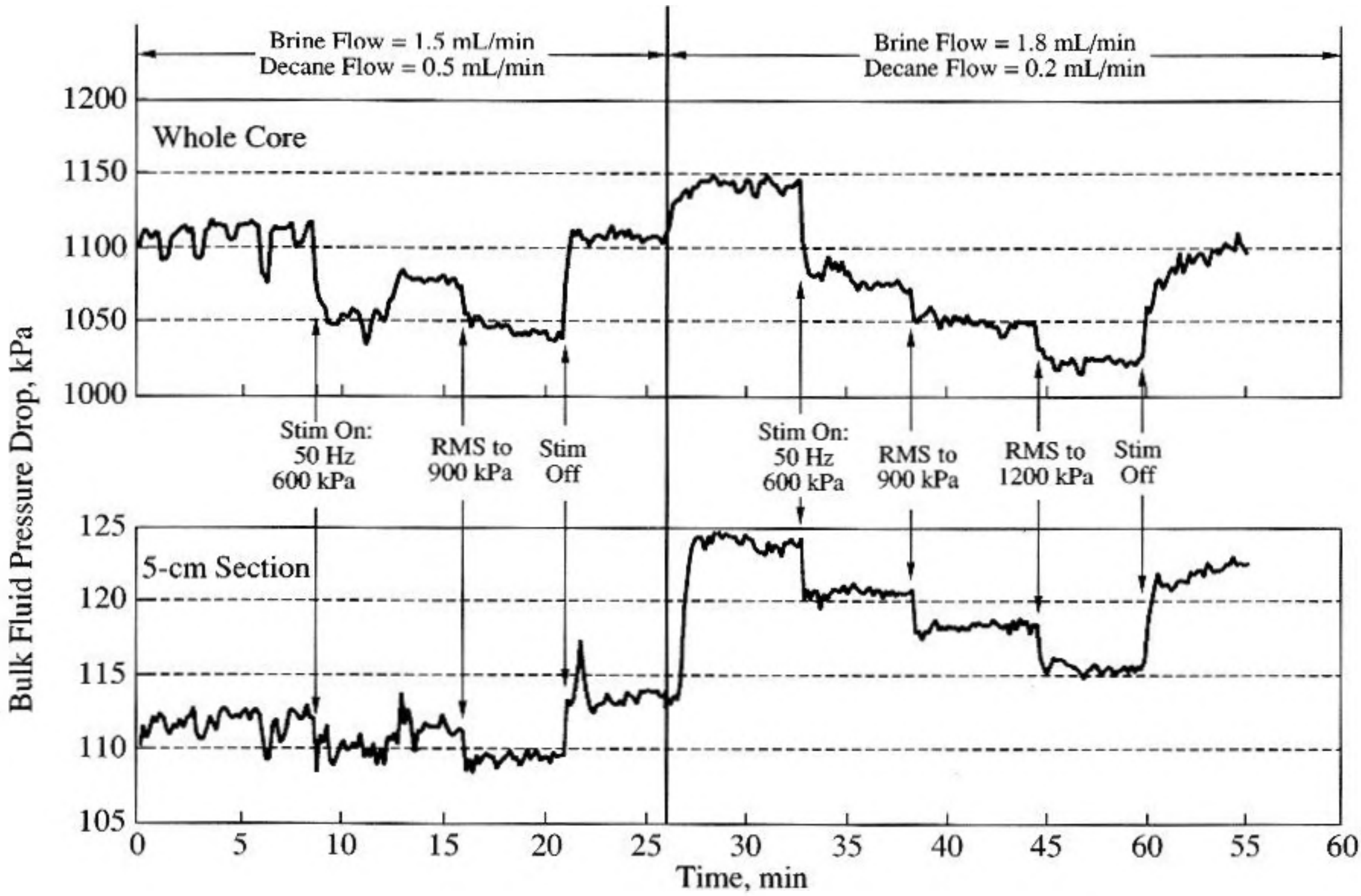

Fig. 3. Changes in bulk-fluid pressure drop during steady-state, 2-phase flow of decane plus brine, induced by 50-Hz stress stimulation at varying amplitudes.

off when the fluid pressure drop leveled off at the new value, as indicated by the "off" arrows. The pressures then decreased toward pre-stimulation values. These stimulation cycles were repeated at least three times for each flow rate, and the same behavior was observed each time. The plot for 50% oil flow shows two of these cycles to demonstrate the repeatability of the behavior. The results for both sets of 2-phase steady-state flow experiments indicate that the wetting-phase and non-wetting-phase relative fluid distribution may have been changed during stress stimulation.

STRESS/STRAIN AND PORE PRESSURE MEASUREMENTS

The various transducers described previously were used to measure the static radial and axial confining stresses and the applied dynamic axial stress during core stimulation. Using strain-gauge measurements on the core, estimates of the static and dynamic values for Young's modulus and Poisson's ratio were obtained for dry and saturated Berea sandstone. Pore pressure was also monitored using an absolute-fluid-pressure gauge connected to one of the taps on the rubber confining sleeve.

Figure 5 shows one example of stress-strain measurements obtained for a Berea sandstone core sample before it was saturated with brine. The static axial stress was increased in four increments up to a maximum of approximately 1400 kPa, and then reduced back to zero in four similar increments. At each static stress level, dynamic axial stress was applied at 10 Hz and 250 kPa RMS amplitude. The plot shows axial stress versus axial strain during this stress cycling. The solid black curve represents increasing static stress up to the maximum and the short-dashed curve shows the return to zero. The open circles on the static curve indicate when dynamic stress was turned on and the black dots indicate when it was turned off. The inset at bottom right shows one example of the dynamic stress/strain, after removing the DC components, measured during each of the eight stimulations. All eight dynamic loops were nearly identical. The open circle on the dynamic data corresponds to the start points on the static curve. When the dynamic stress is turned off, the new static values (black dots) fall inside of the main static stress/strain loop. When the static stress is then increased or decreased, though, the values return to the main static loop. This type of nonlinear hysteretic behavior is typical of rocks [20].

The dashed lines through the static and dynamic stress-strain curves show linear fits to the measured data. The slopes of these lines were used to estimate Young's modulus (E) for this sample of dry Berea sandstone. The dynamic Young's modulus is a factor of 2 larger than the static value, as has been noted by others [21]. Similar data for radial versus axial strain also show hysteresis, but the static and dynamic Poisson's

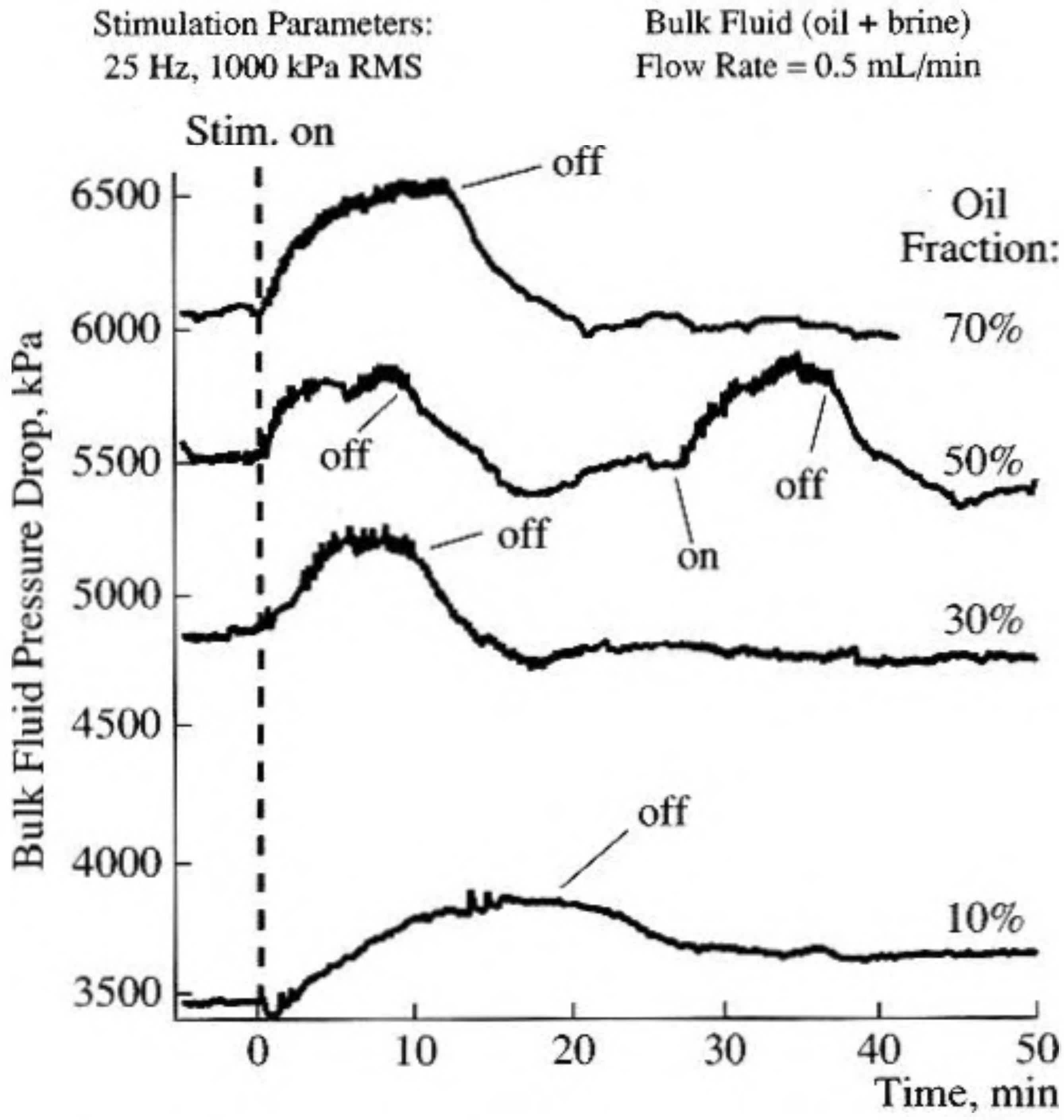

Fig. 4. Changes in bulk-fluid pressure drop during steady-state, 2-phase flow of 10-weight oil plus brine, induced by 25-Hz stress stimulation for different oil-to-water ratios.

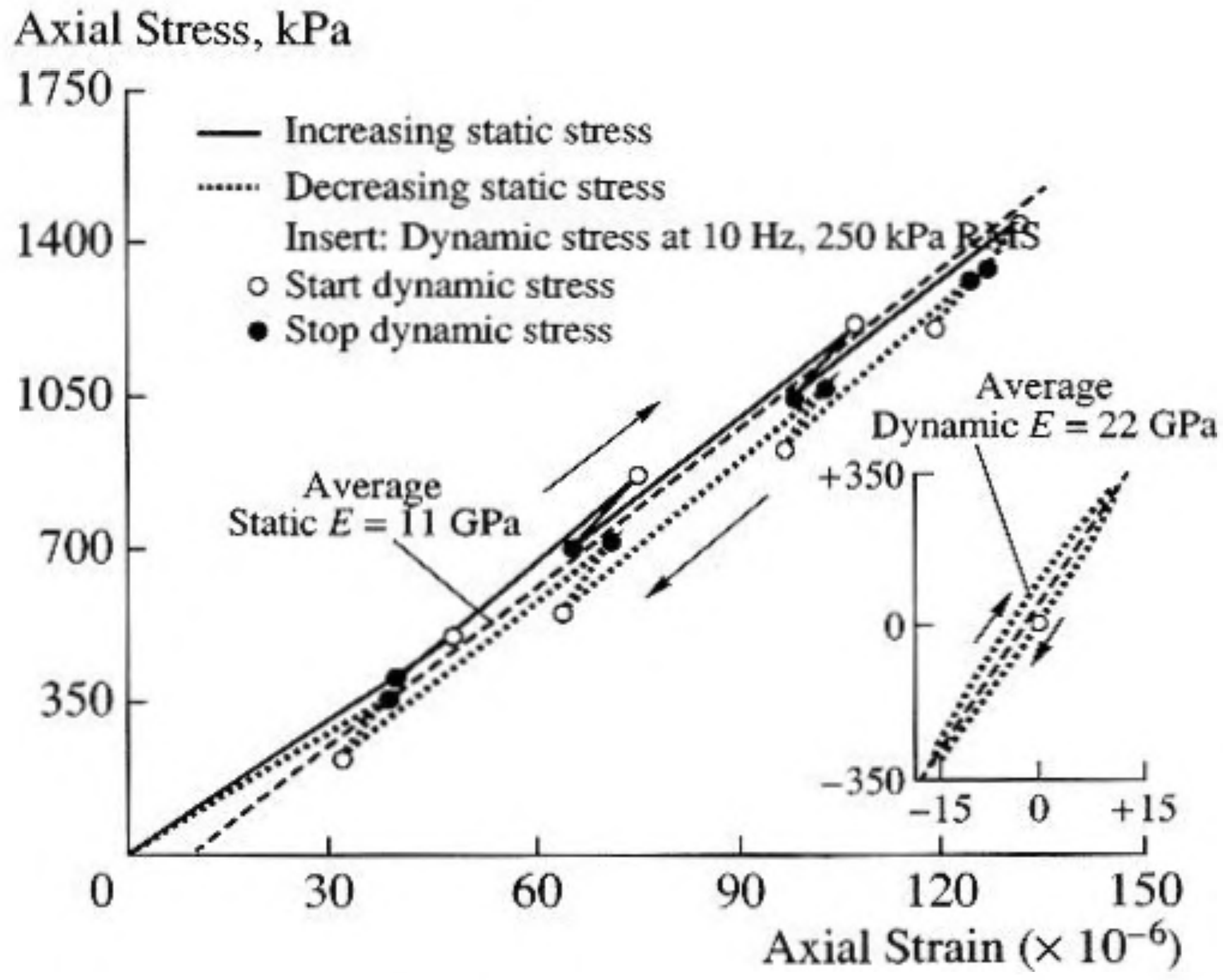

Fig. 5. Static and dynamic axial stress-vs.-strain data obtained for dry Berea sandstone.

ratios are nearly identical. Additional dynamic measurements obtained at different frequencies and amplitudes showed that the dynamic Young's modulus varies only with applied strain amplitude and not with frequency, whereas the dynamic Poisson's ratio varies only with frequency. When the sample is saturated with brine, both the static and dynamic Young's moduli are a factor of 3 to 4 lower than their corresponding values for the dry case. Clearly, elastic properties of the rock are strongly influenced by the frequency and amplitude of dynamic stress oscillations as well as the fluid content of the pore space.

A major practical purpose of the stress, strain, and pore pressure measurement systems is to provide estimates of stimulation parameters that cause observable changes in fluid-flow behavior under laboratory conditions. Downhole stimulation sources to be used for field testing can then be designed to generate similar mechanical stress and/or pore pressure perturbations within the Earth's crust. The mechanical-stress levels used in the laboratory tests ranged from 300 to 1200 kPa RMS, and the equivalent axial strains induced in the core were roughly 3×10^{-5} to 8×10^{-5}, respectively. Altered flow behavior was observed only at RMS stress levels of 600 kPa and above. Because the stimulation was primarily mechanical, pore pressure oscillations are induced through pore volume changes caused by deformational strain of the core's solid matrix. Measuring dynamic pore pressure during stimulated fluid flow is difficult because the tubing connecting the core confinement sleeve to the pressure transducers attenuates the signal when the frequency is higher than about 1 Hz. Instead, estimates for induced pore-pressure oscillations were obtained by measuring the fluid pressure near the center of the core at numerous static axial stress values. To get accurate measurements, the fluid flow inlet and outlet had to be closed to prevent fluid leakage from the core. Figure 6 shows the pore pressure data obtained. Closed-system pressure is a factor of 0.004 lower than the applied axial stress, as indicated by the linear fit to the data. The coupling between matrix deformation and pore pressure will be much weaker when fluid is allowed to escape from the core. Thus, the closed-system measurements represent upper

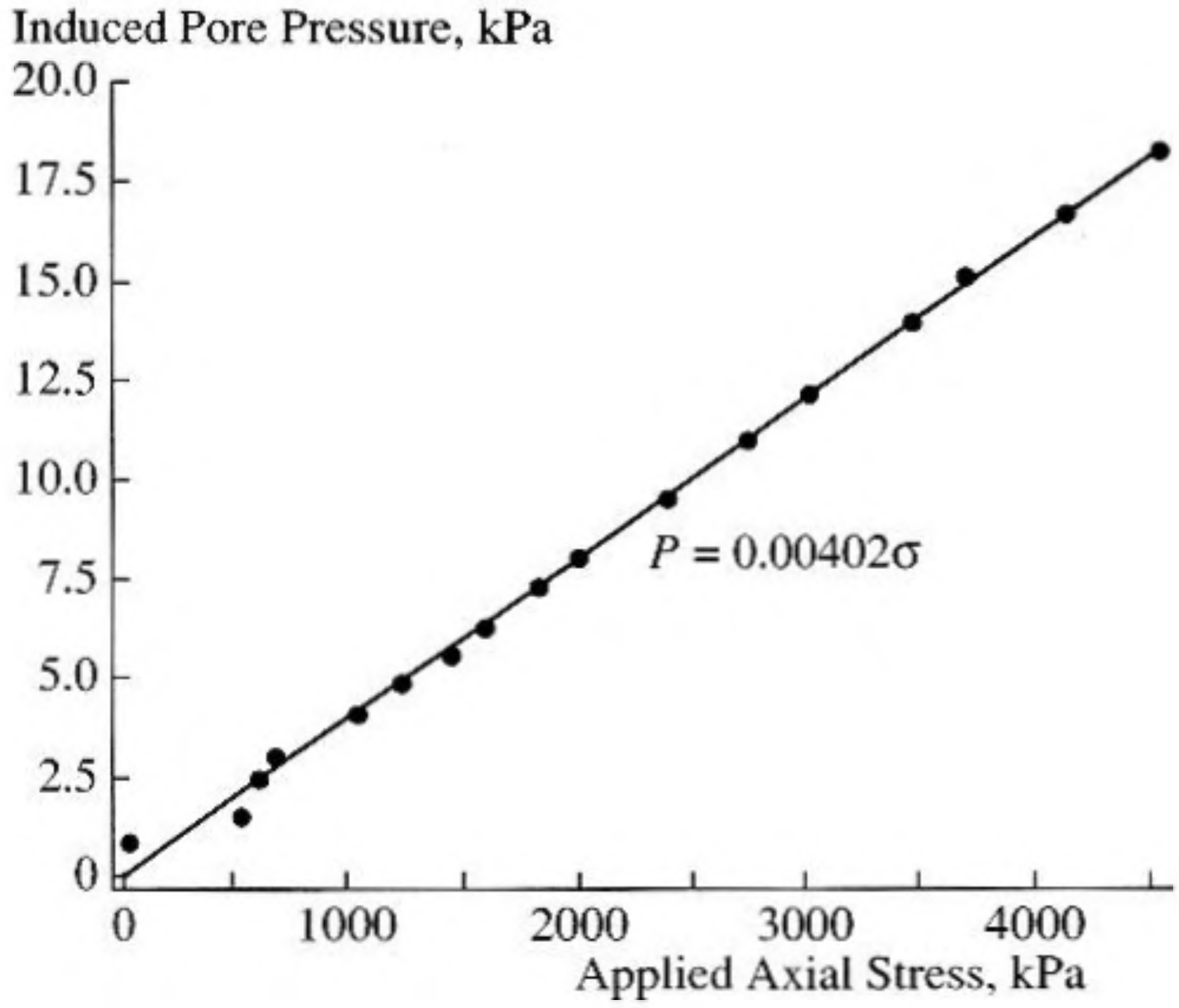

Fig. 6. Pore pressure versus static, axial, mechanical stress for brine-saturated Berea sandstone. Measurements were made with the fluid-flow system closed.

bounds for pore-pressure oscillations during stimulated fluid flow, when the system is open at each end of the core. In other words, during steady-state fluid flow, dynamic axial stress stimulation at an RMS amplitude of 600 kPa (the threshold level at which altered flow behavior was observed) will induce pore pressure oscillations much lower than 2.4 kPa in a 100-md Berea sandstone core.

DISCUSSION

The laboratory results presented here provide compelling new evidence that low-frequency stress stimulation can strongly influence both single-phase and 2-phase porous fluid flow behavior in sandstone cores. Depending on the physical conditions, both long-term (Fig. 2) and short-term (Figs. 3, 4) changes in permeability and/or fluid mobility can be induced. This variable behavior is similar to that observed during numerous field tests on enhancing oil production with downhole seismic sources. Clearly, the stimulated flow phenomenon can be observed over a wide range of size scales, but major questions persist about what the possible physical mechanisms are that control the phenomenon and whether or not they are scale independent. The core-flow tests reported here partially bridge the scale range gap by investigating stress stimulation frequencies below 100 Hz, which is where, in the field, virtually all of the successful, long-range reservoir stimulation tests have been conducted.

The clay fines mobilization experiment is a good example of this. It is well known that ultrasonic waves at 20 kHz and above are effective at removing clay particles from porous rocks. This phenomenon has been investigated before [17, 19] and shown to depend on the wavelength of the excitation relative to the sample's size, geometry, and acoustic properties. Thus, it is somewhat surprising that 50-Hz stress cycling can produce similar effects on core samples that are roughly the same size as those used in the ultrasonics experiments. Because the wavelength at 50 Hz is orders of magnitude larger than the sample size, wave propagation does not occur. The core is simply being strained uniformly as if it were a spring. Motion of clay particles relative to the fluid or porous matrix can occur, though, if local fluid pressure differentials or particle momentum perturbations are being generated within the pore space. Two possible mechanisms that could generate these dynamic effects are 1) phase delays between the solid matrix, clay particle, and fluid motions due to fluid visco-elastic effects, and 2) pore-scale turbulence generated by transient fluid motion around the clay particles themselves. Both mechanisms are supported by the observation that particle mobilization is more effective at either lower absolute pore pressures or lower fluid pressure gradients during flow. This may indicate that a fluid-dynamics-based mechanism is more likely than a mechanical-strain-based mechanism (i.e., pore expansion). Additional modeling and new experiments will be needed to adequately investigate these speculations.

A major practical implication of low-frequency particle mobilization is that a phenomenon that was previously thought to occur only at high frequency and at very short distances (10–20 cm or less) may prove to be useful for improving formation permeability at much larger distances, perhaps up to 1000 m from the stimulation source. This could be used, for instance, to improve the hydrodynamic conductivity of silty groundwater aquifiers using a low-frequency seismic source in a single water well.

The 2-phase flow experiments demonstrated that 1) low-frequency stress stimulation changes the bulk-fluid pressure drop across porous core samples during steady-state flow, and 2) the viscosity of the non-wetting phase relative to the wetting phase determines whether the pressure drop will increase or decrease. Because of the imposed constant-rate, steady-state flow conditions, the pressure changes are in the directions one would expect for increased non-wetting-phase saturation in the core; that is, the ratio of flowing decane (or oil) to flowing brine is increased inside the core by dynamic stress stimulation, even though the injected fluid composition is fixed by the pumps.

One possible explanation for this behavior is that stimulation mobilizes the non-wetting fluid at the expense of previously-mobile wetting fluid, thereby increasing the non-wetting-phase saturation of the bulk fluid flowing through the core. Thus, decane-plus-brine pressures decrease because decane is less viscous than brine and oil-plus-brine pressures increase because 10-weight oil is more viscous than brine. This is a speculation because the actual mobile-fluid saturation in the core before and during stimulation could not be measured in these experiments. The data support this hypothesis, though, if we assume that a single physical mechanism (one that controls fluid phase mobility or, equivalently, the relative permeability of the rock to the non-wetting phase) is responsible for both the decane-plus-brine and oil-plus-brine observations.

One such mechanism is altered matrix wettability. Berea sandstone is a highly water-wet rock, meaning that water will spontaneously imbibe into and flow through the rock more readily than decane or oil. Thus, the connected flow paths through the pore space will favor containing brine over decane or oil, and the relative brine saturation of the core may be significantly different than that of the injected 2-phase bulk fluid. Based on independent empirical observations comparing oil-wet and water-wet formation rocks [22], stress oscillations have been proposed to be capable of temporarily changing a water-wet rock to become more oil wet (and vice versa for an oil-wet rock). This mechanism, then, could change the mobile-fluid composition as oil replaces some of the water in the flowing volume of the rock core. Assuming the flowing portion of the core's pore volume is constant (no change in absolute intrinsic permeability), a change in bulk-fluid composition will change it's effective viscosity, and will thus cause pressure drop changes across the core during steady-state 2-phase flow.

Other mechanisms that could cause effects such as absolute permeability changes or induced emulsification of the 2-phase mixture would also cause pressure drop changes, but these would cause the pressure to change in the same direction regardless of the viscosity of the non-wetting phase. Again, new modeling and experimental efforts will be needed to prove or disprove the altered wettability hypothesis. It is clear, though, that low-frequency stimulation has a profound, repeatable effect on 2-phase porous flow behavior that supports the hypothesis that a change in fluid distribution is being induced inside the core.

Mobilizing non-wetting fluids has been proposed to explain some of the field observations of enhanced oil production caused by downhole seismic sources [3]. Water floods are often used to displace trapped oil pockets, but a large percentage of in-place oil is bypassed by these floods. Stimulation may mobilize the trapped oil by changing the formation wettability and allowing it to be more efficiently swept by the water flood. Thus, prior knowledge of a formation's state of wettability may be an important criterion for selecting candidate fields that are likely to respond well to seismic stimulation.

The dynamic mechanical stress levels used in the core experiments (see Figure 5) are significantly higher than what existing downhole sources produce at distances in excess of 100 m. However, the pore pressure oscillations induced in the core by the applied mechanical stress were extremely low (see Figure 6), probably much less than 1 kPa RMS. For these two reasons, it is likely that pore pressure changes are more important than mechanical strain for inducing enhanced porous flow. Devices that couple energy efficiently to the pore fluids may be preferred over devices that produce primarily elastic strain energy. This remains an open question, however, because mode conversions between various elastic wave types and how these waves couple to the formation pore pressure are strongly influenced by the physical conditions in the fluid-bearing formations.

The one clear target we can define for effective wavefield parameters is that the source frequency range should be low enough to allow energy to propagate to the target zone, which may be up to several kilometers from the source well, with little loss of amplitude due to attenuation in the medium. The laboratory tests discussed above were all performed with stimulation frequencies of 75 Hz or less and are, thus, scaleable to the field. The stress-strain and pore-pressure measurements can provide input to theoretical and numerical models for stimulated fluid flow.

CONCLUSIONS

Laboratory experiments on Berea sandstone cores demonstrated that low-frequency (25 to 75 Hz), axial, mechanical stress cycling at RMS amplitudes of 600 kPa and higher can induce significant changes in single-phase and 2-phase fluid flow behavior through porous media. During single-phase brine flow, dynamic stress stimulation mobilized in-situ clay fines that were partially plugging the pores and increased the absolute permeability of the samples by 15 to 20%. Possible physical mechanisms that could explain this observation are 1) visco-elastic phase delays producing relative motion between the pore matrix, fluid and clay particles, and 2) turbulence and particle agitation caused by oscillating fluid-pressure gradients near the clay particles. During 2-phase, steady-state flow of immiscible decane-plus-brine and oil-plus-brine mixtures, stimulation changed the bulk-fluid pressure drop across the cores in a manner that suggests the relative saturations of the non-wetting (decane and oil) fluids was increased. The viscosity of the non-wetting phase relative to the wetting phase (brine) determines whether the pressure drop will increase or decrease during stimulation. Altered matrix wettability is one physical mechanism that could explain these observations. The data presented are largely empirical and additional experiments and comparisons with theoretical and numerical models will be required to prove or disprove these speculations. Accurate measurements of stress and strain used during the experiments provided estimates of both static and dynamic elastic properties of dry and saturated Berea sandstone. Young's modulus during 10-Hz dynamic stress stimulation is a factor of 2 larger than the static value. When the rock is saturated with brine, both the static and dynamic moduli are a factor of 3 to 4 lower than for the dry case. The mechanical strain of the pore matrix caused by an applied dynamic stress of 600 kPa RMS was roughly 4×10^{-5}. The coupled pore pressure fluctuations induced by this matrix deformation was estimated to be much lower than 2.4 kPa. Existing seismic sources used successfully in the field to enhance oil reservoir production cannot produce stress and strain levels as high as those used in the laboratory, but can produce similar small pore-pressure fluctuations. This may indicate that pore pressure is more important than mechanical strain for enhancing porous flow.

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REFERENCES

1. *Beresnev, I.A. and P.A. Johnson*, Elastic-Wave Stimulation of Oil Production: A Review of Methods and Results, Geophysics , 1994, **59**, 1000–1017.
2. *Nikolaevski, V.N., G.P. Lopukhov, Y. Liao and M.J.* Economides, Residual Oil Reservoir Recovery with Seismic Vibrations, SPE Production and Facilities, 1996, **May**, 89–94.
3. *Kostrov, S.A., W.O. Wooden and P.M. Roberts*, In Situ Seismic Shockwaves Stimulate Oil Production, Oil & Gas J., 2001, **99.36**, 47–52, Sept. 3.
4. *Roberts, P.M., S.A. Kostrov, W.O. Wooden, E.L. Majer and T.M. Daley*, Laboratory and Field Observations of Stress-Wave Induced Changes in Oil Flow Behavior, Expanded Abstracts, 2001 Soc. Expl. Geophys. Annual Meeting, San Antonio, 2001, 8 pp.
5. *Roberts, P.M., I.B. Esipov and E.L. Majer*, Elastic Wave Stimulation of Oil Reservoirs: Promising EOR Technology?, The Leading Edge, 2003, **22–5**, 448–453, invited paper.
6. *Roberts, P.M., A. Sharma, V. Uddameri, M. Monagle, D.E. Dale and L.K. Steck*, Enhanced DNAPL Transport in a Sand Core during Dynamic Stress Stimulation, Environ. Eng. Sci., 2001, **18–2**, 67–79.
7. *Hilpert, M., D. Stopper and G.H. Jirka*, Mobilization of a Residual NAPL Contamination in Porous Media by Sound Waves, *EOS Trans. AGU*, 1996, **77–46**: F204.
8. *Reddi, L.N. and S. Challa*, Vibratory Mobilization of Immiscible Liquid Ganglia in Sands, J. Environ. Eng., 1994, **120–5**, 1170–1190.
9. *Kouznetsov, O.L., E.M. Simkin, G.V. Chilingar and S.A. Katz*, Improved Oil Recovery by Application of Vibro-Energy to Waterflooded Sandstone, J. Petrol. Sci. Eng., 1998, **19**, 191–200.
10. *Hilpert, M., G.H. Jirka and E.J. Plate*, Capillarity-Induced Resonance of Oil Blobs in Capillary Tubes and Porous Media, Geophysics, 2000, **65**, 874–883.
11. *Graham, D.R. and J.J.L. Higdon*, Oscillatory Flow of Droplets in Capillary Tubes, Part 1, Straight Tubes, J. Fluid Mech., 2000, **425**, 31–53.
12. *Graham, D.R. and J.J.L. Higdon*, Oscillatory Flow of Droplets in Capillary Tubes, Part 2, Constricted Tubes, J. Fluid Mech., 2000, **425**, 55–77.
13. *Pan, Y. and R.N. Horne*, Resonant Behavior of Saturated Porous Media, J. Geophys. Res., 2000, **105**, 11021–11028.
14. *Tsiklauri, D. and I.A. Beresnev*, Enhancement in the Dynamic Response of a Viscoelastic Fluid Flowing through a Longitudinally Vibrating Tube, Phys. Rev. E, 2001, **63**, 463 041–463 044.
15. *Lo, W.-C., Sposito, G. and E. Majer*, Immiscible Two-Phase Fluid Flows in Deformable Porous Media, Advances in Water Resources, 2002, **25**, 1105–1117.
16. *Dullien, F.A.L.*, Porous Media: Fluid Transport and Pore Structure, Academic Press, New York, 1979, 396 pp.
17. *Venkitaraman, A., P. M. Roberts and M. M. Sharma*, Ultrasonic Removal of Near-Wellbore Damage Caused by Fines and Mud Solids, Soc. Petrol. Eng. Drilling & Completion, 1995, **10–3**: 193–197.
18. *Roberts, P.M.*, A. Venkitaraman and M. M. Sharma, Ultrasonic Removal of Organic Deposits and Polymer Induced Formation Damage, Soc. Petrol. Eng. J. Drilling & Completion, 2000, **15–1**, 19–24.
19. *Poesio, P., Ooms, G., Van Dongen, M.E.H. and D.M.J. Smeulders*, Removal of Small Particles from a Porous Material by Ultrasonic Irradiation, Transport in Porous Media, 2004, **54**, 239–264.
20. *Holcomb, D.J.*, Memory, Relaxation, and Microfracturing in Dilatant Rock, J. Geophys. Res., 1981, **86-B7**, 6235–6249.
21. *Guyer, R.A., K.R. McCall, G.N. Boitnott, L.B. Hilbert Jr. and T.J. Plona*, Quantitative use of Preisach-Mayergoyz Space to find Static and Dynamic Elastic Moduli in Rock, J. Geophys. Res., 1997, **102**, 5281–5293.
22. *Westermark, R.V., Brett, J.F. and D.R. Maloney*, Enhanced Oil Recovery with Downhole Vibration Stimulation, Soc. Petrol. Eng. 2001 Production and Operations Forum Abstracts, 2001, **SPE 67303**, 13 pp.