Acoustical Imaging and Mechanical Properties of Soft Rock and Marine Sediments (Quarterly Technical Progress Report #15302R07)

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ABSTRACT

During the seven quarter of the project the research team analyzed some of the acoustic velocity data and rock deformation data. The goal is to create a series of ‘deformation-velocity maps’ which can outline the types of rock deformational mechanisms which can occur at high pressures and then associate those with specific compressional or shear wave velocity signatures. During this quarter, we began to analyze both the acoustical and deformational properties of the various rock types. Some of the preliminary velocity data from the Danian chalk will be presented in this report. This rock type was selected for the initial efforts as it will be used in the tomographic imaging study outlined in Task 10. This is one of the more important rock types in the study as the Danian chalk is thought to represent an excellent analog to the Ekofisk chalk that has caused so many problems in the North Sea. Some of the preliminary acoustic velocity data obtained during this phase of the project indicates that during pore collapse and compaction of this chalk, the acoustic velocities can change by as much as 200 m/s. Theoretically, this significant velocity change should be detectable during repeated successive 3-D seismic images. In addition, research continues with an analysis of the unconsolidated sand samples at high confining pressures obtained in Task 9. The analysis of the results indicate that sands with 10% volume of fines can undergo liquefaction at lower stress conditions than sand samples which do not have fines added. This liquefaction and/or sand flow is similar to “shallow water” flows observed during drilling in the offshore Gulf of Mexico.

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Introduction

Seismic velocity data obtained from 2-D or 3-D imaging is primarily used to detect stratigraphic and structural patterns in rocks in the subsurface. In this mode it is utilized as a method of providing a 'static' map of the rocks in their current state. Seismic data can also yield information on the elastic properties of the rock using AVO technologies. 4-D or time lapse imaging, where repeated 3-D surveys are obtained for a volume of rock, has been used as a tool to map changes in pore fluid properties of rocks. For example, 4-D imaging has been used to image fire floods and CO_2 floods during secondary and tertiary recovery operations in oil and gas fields. 4-D imaging has also been used to track the movement of oil-gas-water contacts in reservoirs as production progressed. The question we are attempting to answer in this research is 'can seismic imaging provide information on the rock deformational properties of petroleum reservoirs?'.

Some reservoir rocks, particularly those that are very weak or poorly consolidated, can be severely damaged during drilling or production operations in oil and gas fields. The classic example is the severe compaction and subsidence in the Ekofisk reservoir. Remedial measures to repair damage to the overlying production facilities cost Phillips Petroleum over 1 billion dollars. Traditionally, petroleum engineers (and the geologists and geophysicists working with them) have tended to think of petroleum reservoir as mechanically stable. The pore fluid changes and migrates but they generally view the reservoir rocks as unchanging. In most cases the rock elastically and or plastically deforms during the production and withdrawal of oil and gas. In the case of the Ekofisk Reservoir, the nature of the reservoir rock deformation is amply evidenced from multiple observations. First, there is the striking subsidence, over 16 feet to date, resulting from the compaction over reservoir chalk located 10,000 feet below the surface. Second, infield drilling of core samples of already produced zones indicates that the rock has been severely damaged.

In this study, the research team is attempting to develop a method of correlating different stress conditions to various rock deformational mechanisms and their compressional and shear wave velocity characteristics.

In addition, 'shallow water flows', which is also the subject of this research study, has been attempted to be reproduced in our labs under high confining pressures and pore fluid pressures. Traditionally, in soil mechanics, liquefaction of saturated granular materials has been studied and documented for over fifty years. In oil and gas applications this phenomenum was never a subject of study. Even though weak sand formations have been drilled in the past and are still being drilled, the recent observations in the Gulf Mexico eventually termed shallow water flows was never documented. In this study the team attempted to reproduce liquefaction phenomenum or 'shallow water flows' conditions in a controlled lab environment under high confining pressures and fluid pressures. This approach was deemed necessary if a physical understanding of the compositions of these soft and unconsolidated sediments is a factor in their behavior.

Executive Summary

During this phase of the project the research team began to: 1) analyze some of the acoustic velocity data, and 2) continued an investigation of the deformation of sand at high pressures to simulate the shallow water flow problem. One of the goals of the study is to create a series of `deformation-velocity' maps for each of the various rock types in the project. The deformation-velocity maps involve correlating rock damage mechanisms, e.g., compaction, dilation etc., to their specific acoustic velocity signatures. By making such a host of such correlations the research team will be able to predictively determine the type of damage and its specific acoustic compressional and shear wave signature when the rock undergoes specific changes in effective stress (for example during drawdown production from an oil and gas reservoir). In this report the research team presents some of the initial compressional and shear wave velocity data on Danian chalk. This high porosity, weakly cemented chalk, is thought to be an excellent analog to the Ekofisk chalk of the North Sea which has created severe compaction and subsidence problems for the petroleum industry. During a hydrostatic compression experiment the Danian chalk exhibited remarkable changes as the pressure increased. Some of the preliminary data indicates that the acoustic velocities in the chalk decreased by as much as 200 m/s during the initial onset of damaging compaction. In addition, the research team continued to analyze results from the sand deformation experiments conducted at confining pressures. These sand experiments are designed to reproduce the problem of shallow water flows which have been so problematic for the petroleum industry conducting deepwater drilling operation in the U.S. Gulf Coast. Preliminary experiments indicate that liquefaction, which is thought to be analogous to the shallow water flow problem, can occur at high confining pressures in sand. Some of the experiments were conducted on Oil Creek sand with different amounts of fines added to the sand. The preliminary results suggest that sands with 10% added fines can undergo liquefaction at lower stress conditions than sand samples which do not have fines added.

Experimental

Chalk Acoustic Characteristics

Figures 1 through 4 shows an example of the deformation and velocity data that will be needed to complete the deformation-velocity map for the Danian chalk. Figure 1 presents the hydrostatic compression stress-volumetric strain curve. The initial section of the curve (0 to 2100 psi confining pressure) is steeper than later sections of the curve. This initial portion is generally associated with elastic (or more realistically semi-elastic) deformational behavior. Above 2100 psi confining pressure, the rock underwent yielding and began to exhibit increased ductility. The stress-volumetric strain curve continues to work hardens until the experiment was terminated at 9000 psi confining pressure. Figure 2 shows the compressional and shear wave velocities associated with the hydrostatic experiment seen in Figure 1. These velocities show a remarkable pattern. Initially, both the compressional and shear wave velocities increase. This increase in velocity is typically associated with elastic deformation. As stress is increased on the rock framework, both grain-to-grain stresses are increased and microcracks and some pore spaces closed. Both effects would result in increased compressional and shear wave velocities. After hydrostatic yielding has occurred in the chalk, at around 2100 psi confining pressure, the acoustic velocities begin to decrease. The decrease is large – almost 10% of the absolute velocities of the chalk. Figures 3 and 4 are plots of the compressional and shear wave velocities enlarged to show the large velocity changes in the chalk. As can be seen in Figure 3 the compressional wave velocity decreases from 2300 m/s down to 2100 m/s past the hydrostatic yield point. Figure 4 indicates that the shear wave velocity decreases from 1300 m/s down to 1100 m/s. These velocity decreases are attributed to the process of pore collapse in the chalk sample. In order for a lithified, cemented, porous rock to compact the external stresses must cause a fracturing of the grain-to-grain cements within the rock. The decoupling of grains and simultaneous fracturing of grain contacts and cements is thought to be the causative mechanism for the decrease in acoustic velocities (Scott et al., 1998). As the deformational process continues increased stress is needed to continue this compaction process. At around 5000 psi confining pressure both the compressional and shear wave velocities begin to increase again (Figures 2, 3, and 4). Note that there is no discernible change in the slope of the stress-volumetric strain curve (Figure 1) – it continues to exhibit increased work hardening. Scott et al., (1998) attributed this increase in velocities to the recontact of the pore collapsed grains. In critical state soil mechanics, this phase is referred to as normal consolidation.

Unconsolidated Sediment Liquefaction at High Pressures

The research team has continued working on the liquefaction of Oil creek sand. As noted in a previous report (the fifith quarterly report), sands undergoing undrained triaxial testing exhibit two distinctly different deformational behaviors. Figure 5 shows the idealized undrained stress pathways curves for a sand sample (starting at point f) at a low confining pressure and one at a high confining pressure (starting at point b). The sand sample at low confining pressure requires an increased stress until it achieves failure on the critical state line. The high confining pressure sand sample will exhibit an initial semi-elastic deformation (points b to c) at which point it will begin to soften (from points c to d). This softening is generally associated with the instability associated with liquefaction. With continued deformation, this sand sample will begin to work harden along the critical state pathway (from points d to e in Figure 5). Preliminary data collected by the research team indicates that the strength of sand sample and the conditions for the onset of the instability associated with liquefaction are dependent upon, among other factors, the amount of fines. Figure 6 illustrates a series of experiments, all starting with approximately the same initial porosity (43%) but which had different amounts of fine sand added. The results indicate that as fines are added the strength needed for liquefaction is slightly lower than if fines are not present. The primary reason for examining the addition of fines at this point in the study is that actual marine sands have a wide range of grain sizes. A well sorted Oil Creek sand may not be representative of the grain sizes of a marine sediment. An Oil Creek with a range of sand grain sizes (especially the addition of fines) may be a much better approximation. Figure 7 shows a schematic of the evolution of the pressures/stresses during an undrained triaxial experiment. The stress-strain curve (the top diagram in Figure 7) shows an initial semi-elastic deformation followed by yielding and strain softening typically associated with the onset of instability in the sand and the onset of liquefaction. The pore pressure response is plotted in the second diagram of Figure 7. It indicates that as the deformation process continues the pore pressure will increase during both the initial loading (semi-elastic phases) and during the instability and strain-softening. During the work hardening phase, which is the last stage of deformation, the pore pressure begins to decrease. Figure 8 is a plot of the actual data for an Oil Creek sand sample at 2000 psi confining pressure and 1000 psi pore fluid pressure. Figure 9 shows the pore pressure response for the Oil Creek sand with various amounts of fines added. It indicates that as fines increase the sample exhibits a high increase in pore fluid pressures, as deformation proceeds.

The research team is currently in the process of 1) preparing to conduct the acoustic tomographic imaging of the Danian chalk utilizing the methods outlined in Task 6, 2) to measure the compressional and shear wave velocities in the sand samples during instability (liquefaction), and 3) to complete the deformation-velocity map for the Danian chalk.

References

Scott, T.E., Zaman, M.M., and Roegiers, J.-C., (1998) Acoustic velocity signatures associated with rock-deformation processes, Journal Petroleum Technology, (SPE39403), Vol. 50, No. 6, pp. 70-74.

Project month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1 Obtain Rock Samples	X	X																						
Task 2 Construct New Acoustic Platens	X	X																						
Task 3 Calibrate Equipment	X	X																						
Task 4 Prepare Sandstone & Chalk Samples		X	X	X																				
Task 5 Construct Lateral Acoustic Sensors		X	X	X																				
Task 6 Reconnaissance Test Chalk & Sandstones				X	X	X																		
Task 7 AE Hypocentral Location & Full Dynamic Tensor							X	X	X	X	X													
Task 8 Correlate Static & Dynamic Parameters											X	X												
Task 9 Test Sand Pack Samples													X	X	X									
Task 10 Ultrasonic Tomography on Sandstone & Chalks																X	X	X	X	X				
Task 11 Make Deformation Velocity Maps																					X	X		
Task 12 Final Report																							X	X

Table 1: Project time line with seventh quarter targets highlighted

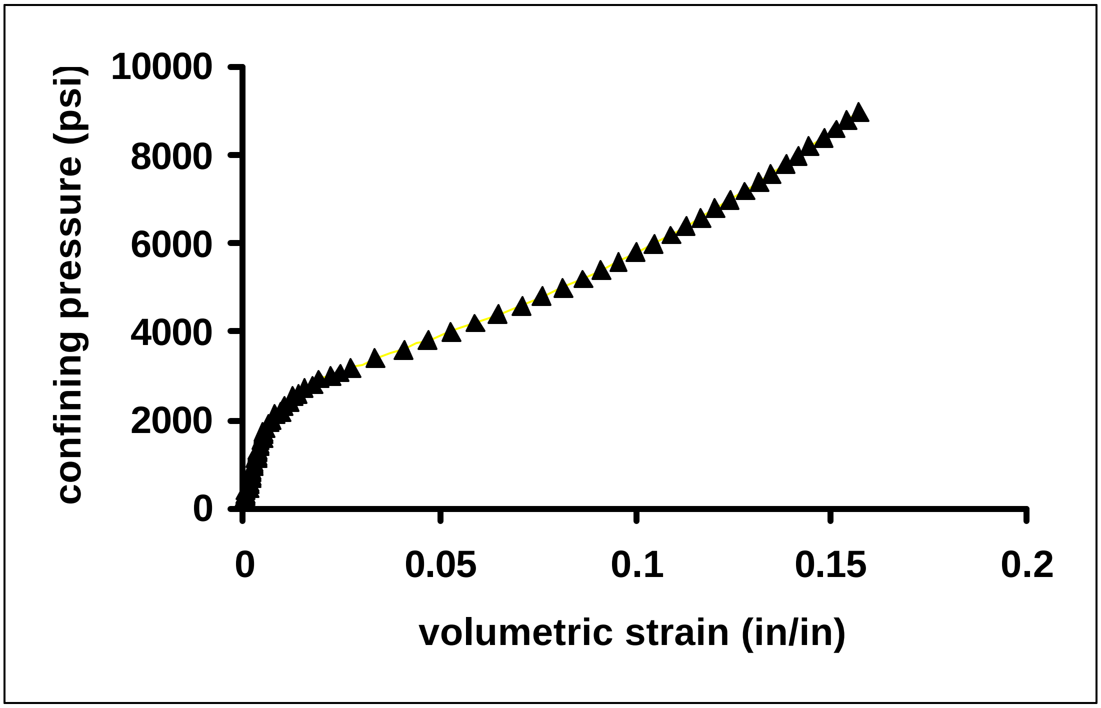


Fig.1. The confining pressure-volumetric strain plot for the Danian chalk undergoing hydrostatic deformation.

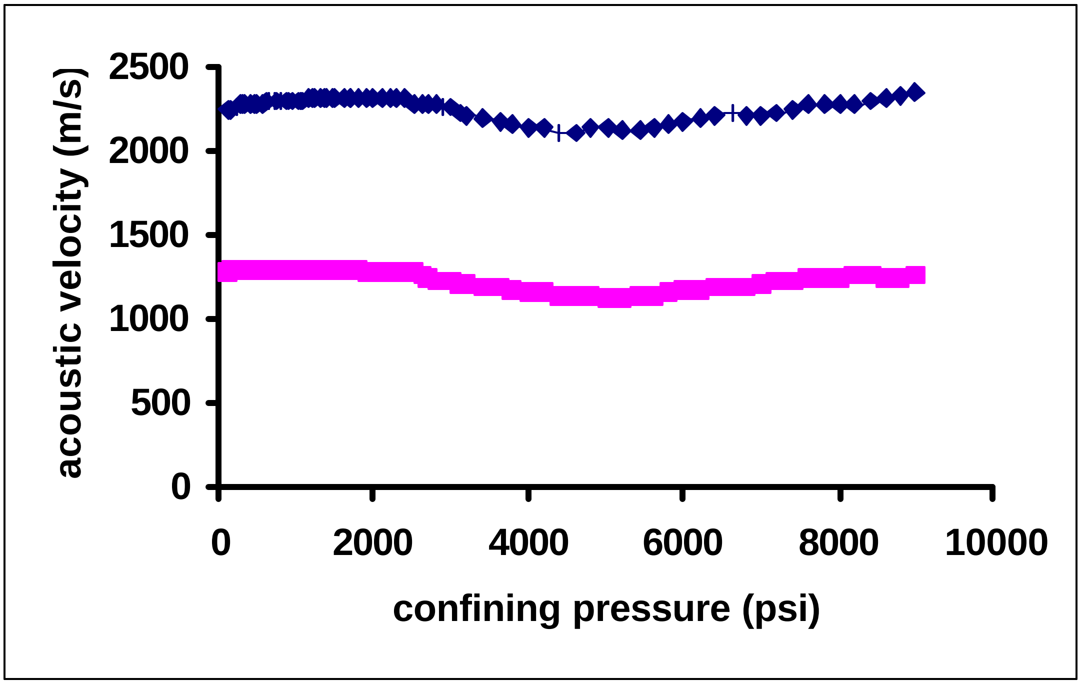


Fig. 2. Compressional and shear wave velocities during the hydrostatic compression experiment.

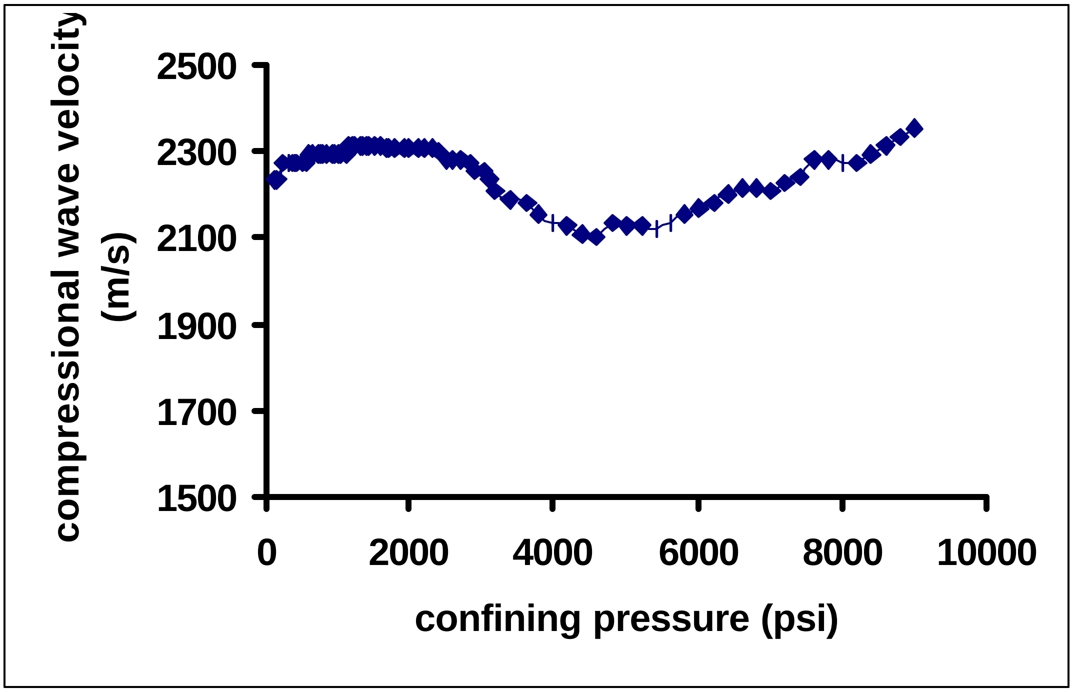


Fig. 3. A plot with an expanded scale of the compressional wave velocities during the hydrostatic compression experiment. Note the velocity decrease after ductile yielding (point b) and the velocity increase during later work hardening (point c).

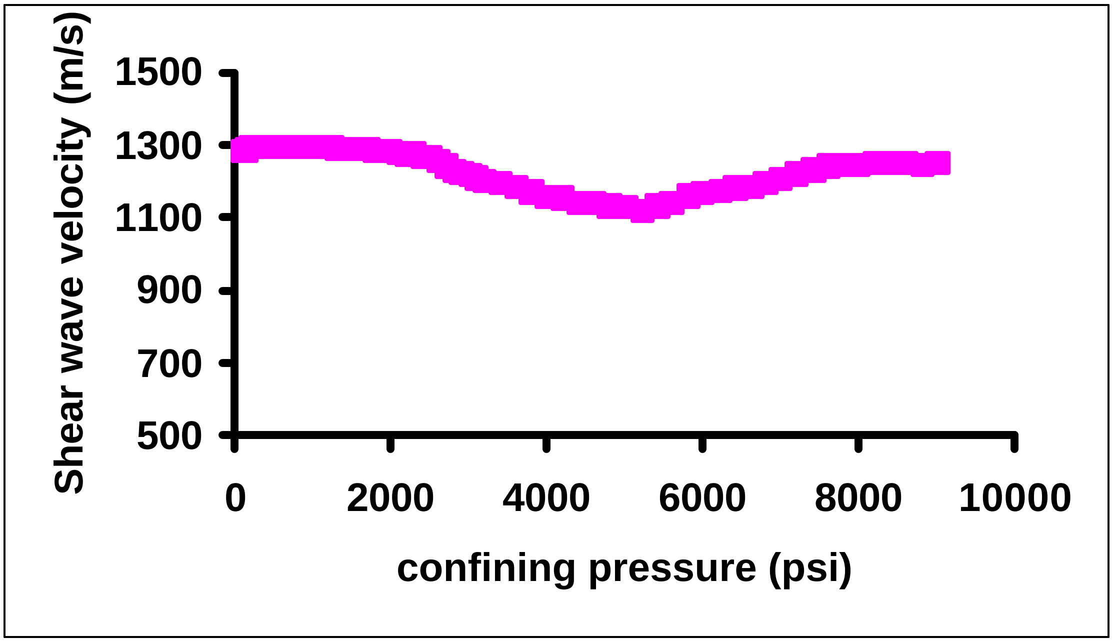
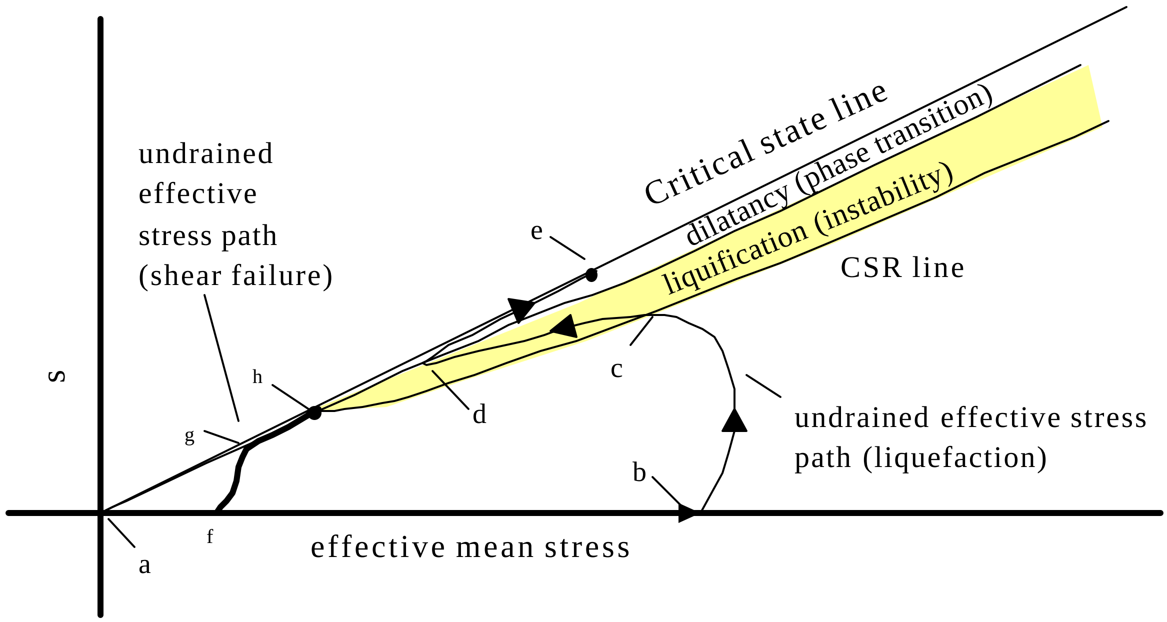


Fig. 4. Expanded scale of the shear wave velocities during the hydrostatic compression experiment. Note the velocity decrease after ductile yielding (point b) and the velocity increase during later work hardening (point c).



mean stress $P_m = \frac{s_1 + s_2 + s_3}{3}$

effective mean stress $P_{me} = P_m - P_p$

shear stress $q = \frac{s_1 - s_3}{2}$

Fig. 5. An idealized schematic of an undrained triaxial pathway for a sand sample.

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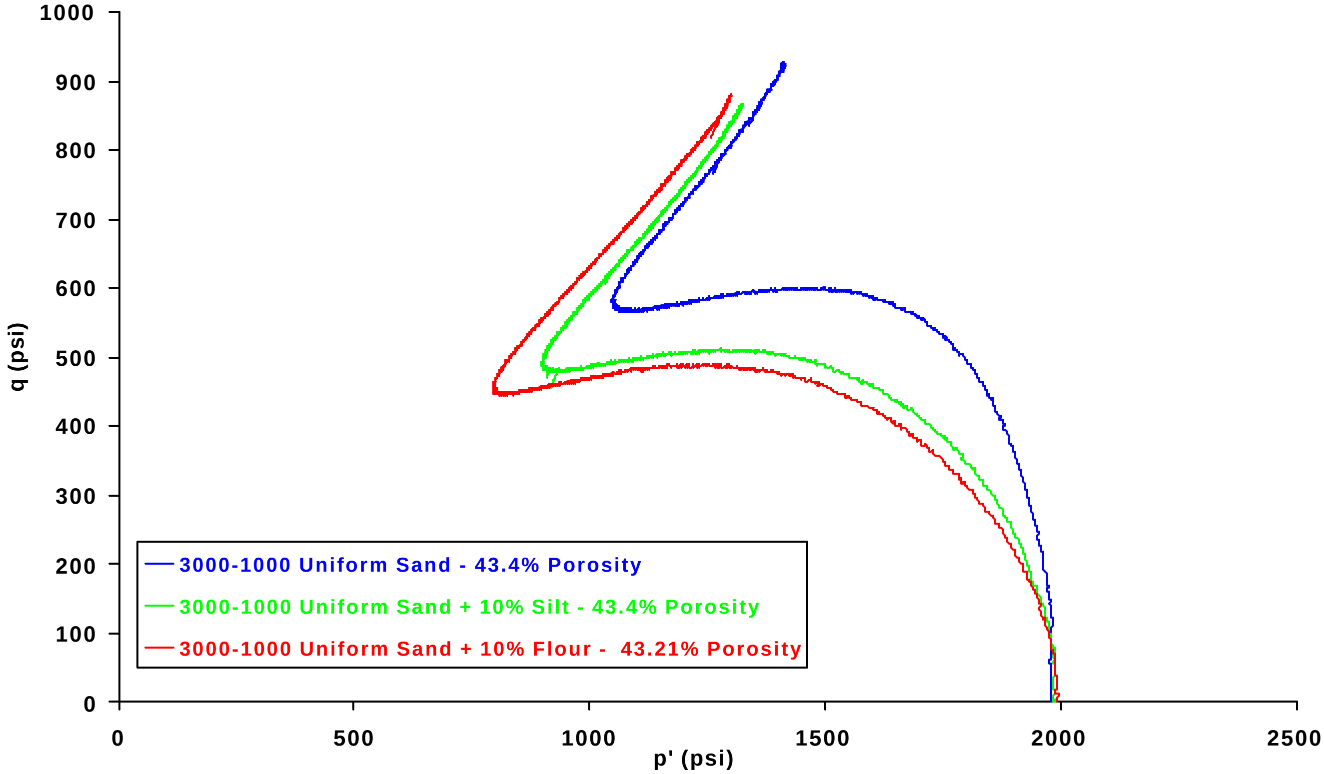

Fig. 6. A plot of the preliminary results from undrained triaxial pathways for three sands with different amounts of fines added.

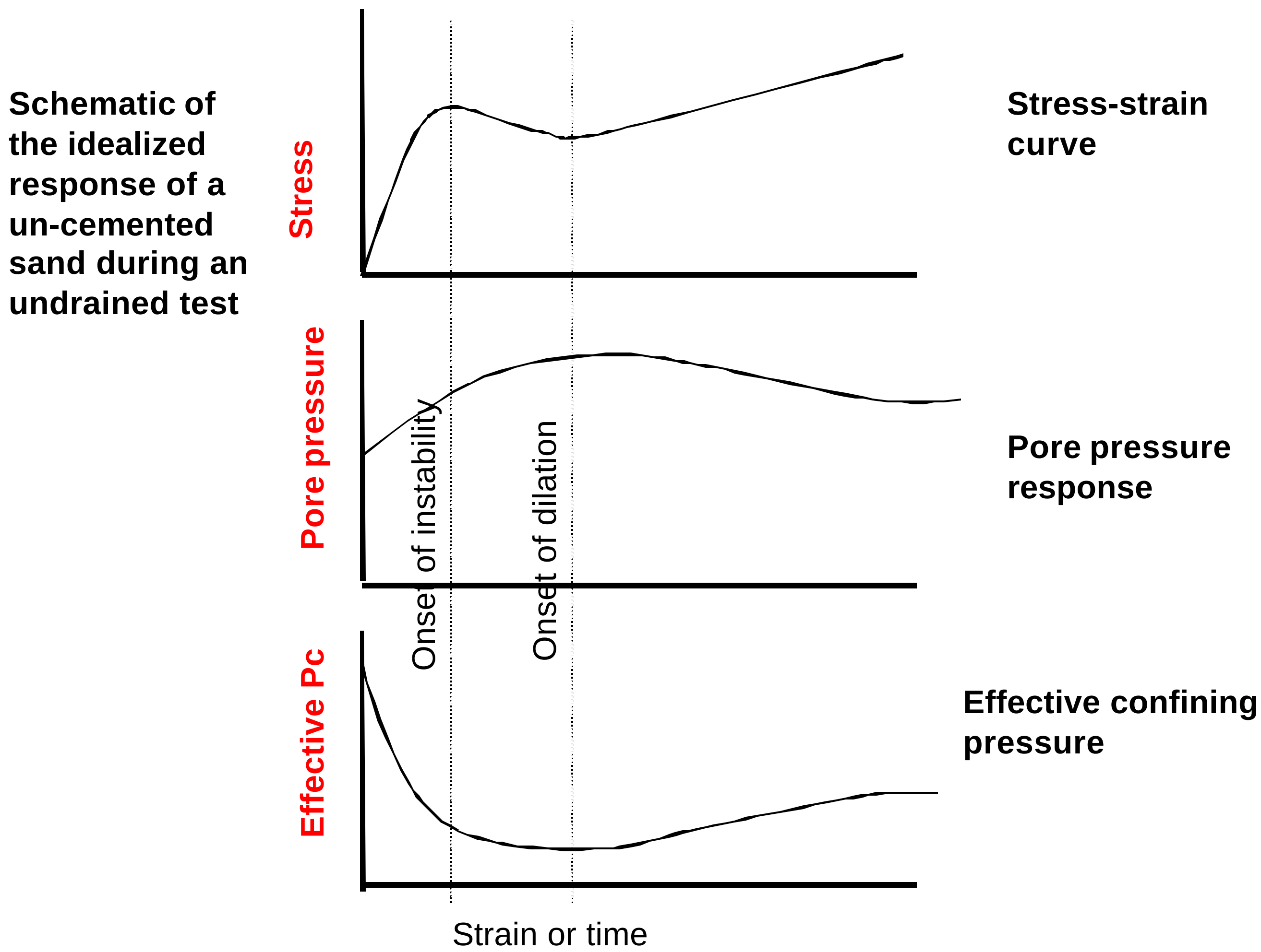

Fig. 7. A schematic of the idealized response of an uncemented sand during an undrained triaxial compression experiment.

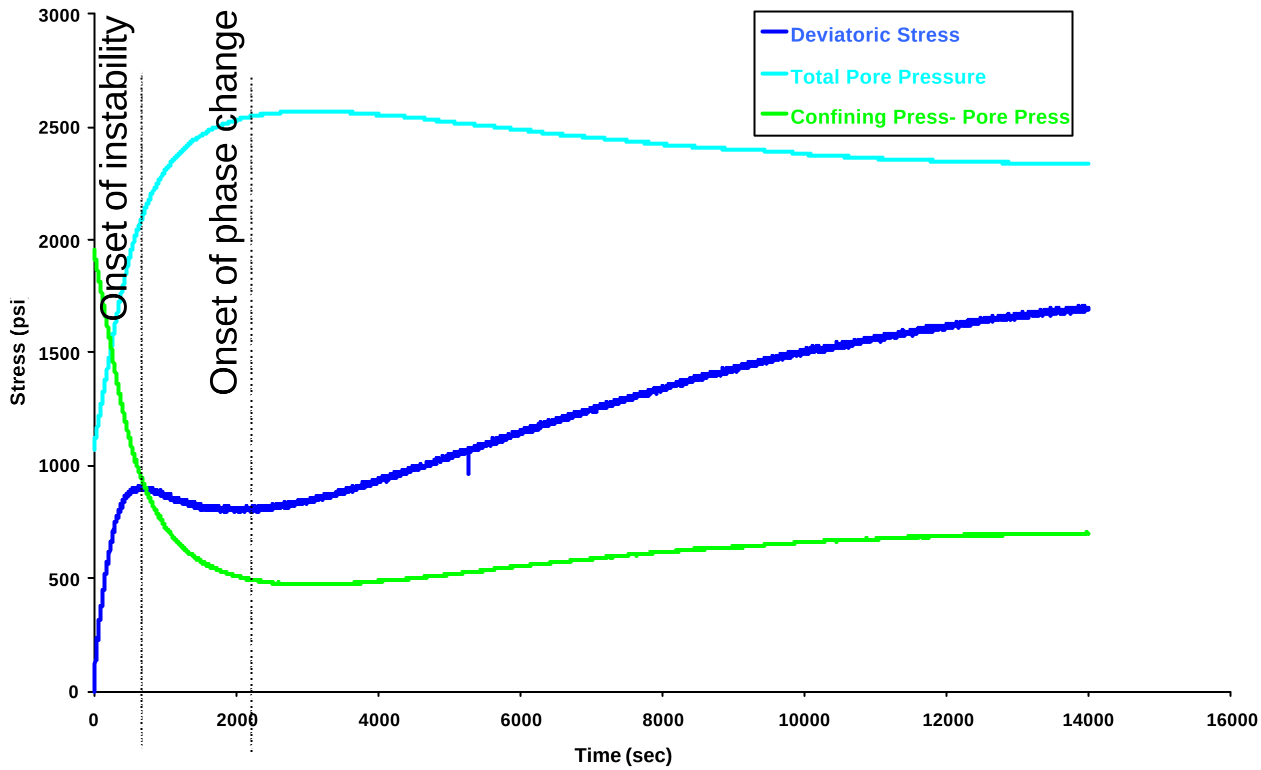

Fig. 8. A plot of the deviatoric stress, the confining pressure, and pore pressure changes during a liquefaction experiment.

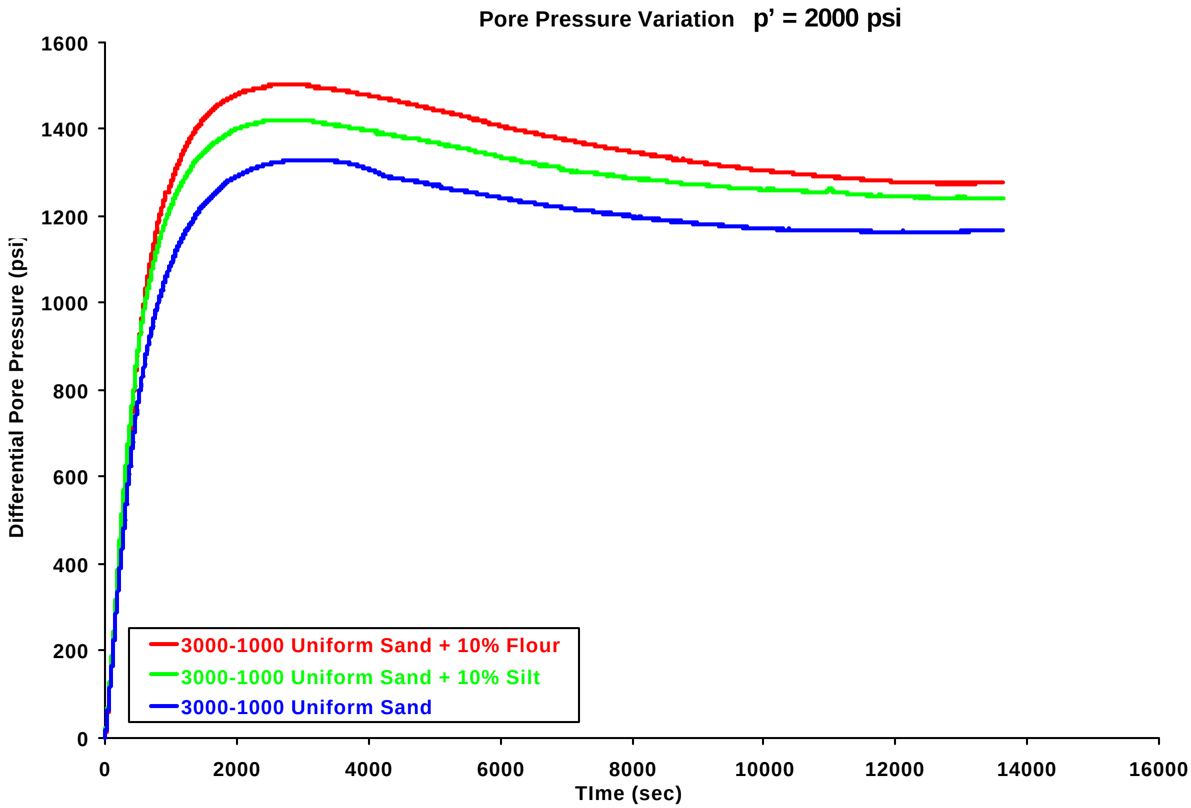

Fig. 9. Preliminary results from pore pressure-times curves for three different mixtures of Oil Creek sand as finer materials are added to the sand.