Acoustical Imaging and Mechanical Properties
of Soft Rock and Marine Sediments
(Quarterly Technical Progress Report #15302R04)

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ABSTRACT

During this phase of the project the research team concentrated on acquisition of acoustic emission data from the high porosity rock samples. The initial experiments indicated that the acoustic emission activity from high porosity Danian chalk were of a very low amplitude. Even though the sample underwent yielding and significant plastic deformation the sample did not generate significant AE activity. This was somewhat surprising. These initial results call into question the validity of attempting to locate AE activity in this weak rock type. As a result the testing program was slightly altered to include measuring the acoustic emission activity from many of the rock types listed in the research program. The preliminary experimental results indicate that AE activity in the sandstones is much higher than in the carbonate rocks (i.e., the chinks and limestones). This observation may be particularly important for planning microseismic imaging of reservoir rocks in the field environment. The preliminary results suggest that microseismic imaging of reservoir rock from acoustic emission activity generated from matrix deformation (during compaction and subsidence) would be extremely difficult to accomplish.

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INTRODUCTION

During this project quarter the research team concentrated on obtaining the acoustic emission signatures of high porosity sandstones, limestones, and chalks undergoing deformation at high pressures. Acoustic emission activity is generated as elastic waves from the microscopic deformation of grains, grain cements, creation of microcracks, and collapse of pore spaces. These elastic waves can be detected by commercial acoustic emission recorders. The goal of the AE research in this project is to identify the signature and intensity of acoustic emissions generated during deformation of a rock and correlate it to a specific deformational mechanism (e.g., compaction or shear fracturing). Acoustic emission activity studies of rock have been conducted since Scholz (1968). The importance of detecting this activity in the natural setting has been recognized by the oil and gas industry as they are beginning to monitor the microseismic activity of reservoirs during the production of hydrocarbons and during water flooding operations. Some of the companies operating in the North Sea, such as Phillips Petroleum, have done some limited acoustic/microseismic monitoring of reservoirs to determine if the subsidence has an acoustic emission signature and where it is located within the reservoir (Rutledge et al. 1994). Those initial results indicate that microseismic activity is being generated during localized shearing and reactivation of faults as opposed to being evenly distributed within the reservoir due to uniform compaction and subsidence. In such cases 3-component geophones were cemented in the casing of the wellbores for a limited amount of time (Rutledge et al. 1994). In the future it may be possible to have permanent seismic networks for both active imaging (i.e., tomography, or reflection or refraction surveys) and for passively imaging acoustic emission (microseismic) information to detect and map out reservoir rock damage within the reservoir.

EXECUTIVE SUMMARY

The experimental program, during this phase of the project, was designed to provide acoustic emission (AE) data on a variety of weak and soft rocks with the goal of building a database useful for designing microseismic monitoring of oil and gas reservoirs. Rutledge et al. (1994) conducted a limited microseismic monitoring program to image shear faulting in a producing reservoir. A series of triaxial compression experiments were conducted on each rock type at 1000 psi confining pressure. Each rock type was deformed until it achieved failure or its ultimate strength. The first rock type tested was the Danian chalk, which is an analog to the Ekofisk chalk and many carbonate reservoirs. The rock had low strength during ductile compaction. Surprisingly, the acoustic emission activity was very low in both amplitude and in the number of events generated during this plastic deformation. The low level of activity would make acoustic emission imaging an extremely difficult, if not impossible, task. Several repeat tests were conducted on this chalk to verify that the results were inherent to the rock type and not due to unforeseen equipment problems. After obtaining these initial results the research team decided to amend the testing program to the other rock types including Oil Creek sandstone, Indiana limestone, and Cordoba Cream limestone. Berea sandstone samples were cored, cut, and tested during this phase because its acoustic emission behavior is well documented. A comparison of the AE data from the Berea sandstone versus the Danian chalk is most informative. Using the exact same experimental setup the Berea sandstone exhibited over 130,000 events whereas the Danian chalk generated only 2300 events under the same deformational conditions. Subsequent experiments on other sandstones and limestones indicated that all the high porosity carbonate rocks (e.g., the chalks and limestones) exhibited much lower acoustic emission activities during deformation than did the sandstones. Respectively, the Danian chalk, Cordoba Cream limestone, and Indiana limestone exhibited 2300, 80, and 1700 events. The sandstones were much higher with 130,000 and 280,000 events detected for the Berea and the Oil Creek sandstones, respectively. Besides the observation that the carbonates exhibited much lower AE activities than did the sandstones, some other preliminary observations could be made from this initial limited data set. A higher ultimate strength of the rock type would not seem to be a unique indicator of higher AE activity. Both the Indiana limestone and the Berea sandstone had similar ultimate strengths at yielding but the acoustic emission activity was much lower in the Indiana limestone. Also, the grain sizes of the Indiana and Cordoba Cream limestones were similar to the Berea and Oil Creek sandstones. However, these generated vastly different AE activities.

These preliminary results are important as they suggest the acoustic emission monitoring of matrix deformation of carbonate rocks during reservoir deformation may be very difficult. In the case of Rutledge et al. (1994) they concluded that the microseismic activity they were monitoring was from shear fault activation during production of the Ekofisk and not from the matrix compaction. The experimental results from this study suggest that the low level of acoustic emission activity may be common to high porosity carbonate rocks. The acoustic velocity (seismic survey) imaging appears to be a much more promising avenue. These experiments will be conducted in the next phase.

EXPERIMENTAL

Experimental Equipment

Acoustic emission (AE) systems generally work in two distinctly different modes. In one mode, the AE events are captured and characterized according to AE parameters such as their amplitude, duration, number of counts, energy in the event, and rise time. This is generally accomplished by a high speed DSP processor in the system. The data throughput is very fast as the resulting data, e.g., duration or amplitude, are directly stored on the PC and the acoustic waveform data is discarded. In the second type of AE mode the complete event waveforms are captured and stored on the PC for later retrieval. This mode of operation is very slow because of the large data files. This slows data throughput so that only a fraction of the waveforms generated by deforming rock can be stored. In the Keck Geomechanical Acoustic Imaging System both systems are utilized (Figure 1). During these tests AE data was obtained by monitoring the rock sample primarily with the 24-channel Mistras System and an 8-channel Spartan AT AE System (from Physical Acoustics Corporation). After meeting an amplitude threshold criterion (in these tests it is set at 40 db) the signals are characterized according to AE parameters such as amplitude, duration, number of counts, energy, etc. Each AE event is also time stamped to within 50 nsec of its occurrence. Physical Acoustics Corporation 1220A preamplifiers are coupled in line with every acoustic transducer exiting the pressure vessel. Preamplifiers are designed to boost the low level millivolt acoustic signals. These amplifiers have switchable gains from 40 to 60 db and have bandpass filters from 100 to 1200 KHz. The plug in filters are designed to bandpass the wavelengths of interest in the testing program and screen out sources of acoustic noise. A 15-channel Vallen Acoustic Emission System (Figure 1) was utilized to record some of the waveforms. This waveform data is particularly important in determining the settings of the Physical Acoustics Corporation AE systems. So a series of reconnaissance tests were conducted to record some waveforms to determine what the amplitude, duration, and hit lockout time settings should be on the Mistras and Spartan AE Systems before conducting the more controlled tests. A preamplifier gain of 40 db was utilized for all AE systems. The acoustic sensors used in these tests were described in the first DOE quarterly technical progress report (15302RO1). They are designed to acquire acoustic emission signals within a bandwidth of from 100 to 1200 KHz.

During this task the research team also constructed and tested an acoustic emission feedback loop control system so that samples will be deformed at a constant rate of acoustic emission. Figure 2 shows a diagram of this system. The AE hypocentral location methods require that the AE be 'discrete,' i.e., distinctly separate events. During a standard triaxial or unconfined compression experiment at a constant strain rate the acoustic emission rate will increase up to the point (generally near the failure strength of the rock) until the system saturates and the AE events merge into a continuous background. The feedback control system worked well when tested on Berea sandstone.

Experimental Results

After modifying and testing the new AE systems in the Keck Geomechanical Acoustic Imaging System a series of Danian chalk samples were prepared for triaxial testing and AE data acquisition. However, when the AE feedback system was utilized on Danian chalk the system failed to operate properly. An analysis and subsequent investigation by the research team indicated that: (1) the AE activity had very low amplitude levels in the Danian chalk, and (2) that very few events were even acquired and stored. The low level of activity and insufficient number of hits recorded on multiple channels made the location of AE events in the chalk extremely difficult to accomplish. Subsequent repeat testing indicated the low level of AE activity was due to natural characteristics of the rock type and not due to problems with the experimental equipment. Researchers were first concerned that the AE events were releasing energy at frequencies outside of the 100-1200 bandpass region for which both the preamplifiers and piezoelectric sensors had been set up. So the equipment was modified to include a 0-5000 Hz accelerometer (see Figure 1) which was mounted on top of the load frame. This modification was designed to detect low frequency acoustic emission activity. Repeat testing on the Danian chalk indicated that the AE recorded was at the high frequency (ultrasonic) and not at the low frequency. The lack of high amplitude AE of sufficient intensity for AE location resulted in some consternation to the research team as Task 7 was to be dedicated to the acquisition of AE for hypocentral location in the Danian chalk.

The research team could not locate any reference literature on AE behavior of chalk and limestones whereas they did locate numerous experiments on sandstones (see detailed reference list). AE activity has been extensively studied in granites and gneisses (Carlson and Young 1993; Lockner et al. 1977; Lockner and Byerlee 1978; Sondergeld and Estey 1981; Dowding et al. 1985; Yanigadani et al. 1985; Spetzler and Mizutani 1986; Nishizawa et al. 1990; Lockner et al. 1991), in coal (Chugh and Heidinger 1980; Khair and Hardy 1984), andesite (Nishizawa et al. 1985), pyrophyllite (Spetzler et al. 1981), sandstone (Lockner and Byerlee 1977; Zang et al. 1996), and quartzite (Hallbauer et al. 1973).

The team concluded that the best approach at this juncture of the testing program was to conduct a series of constant strain rate experiments while acquiring AE data on all the rock samples in the test program. First, this would allow the researchers to compare AE activities of compositionally diverse rock types while they were deformed under the same controlled experimental conditions. This would be a unique study in its own right and within the guidelines of the proposed research program. Once acquired, that data can then be used to select a more appropriate rock for the AE hypocentral location experiments. The research team also could not locate studies comparing AE activities in diversely different rock types at high pressures. Given these observations the research team concluded that a series of AE experiments comparing sandstones, limestones, and chinks at the same set of deformational conditions could provide valuable insight into the types and mechanisms of the AE of different rock compositions, porosities, and grain sizes.

During this phase of the project a series of acoustic emission experiments were conducted on the high porosity sandstones, limestones, and chinks. The rock core samples were subjected to triaxial stress deformations and the acoustic emission activity was recorded as the samples were deformed to the point where either brittle shear failure occurred or a significant plastic deformation was evidenced. The first rock type tested was the Danian chalk. This rock type is thought to be best representative of the deformation of chalk formations like the Ekofisk chalk in the North Sea. The core sample was tested under triaxial stress conditions at a confining pressure of 1000 psi. The results were somewhat surprising. The acoustic emission activity

was very quiet as compared to that generally observed in sandstones and granites (see references previously listed). Both the acoustic amplitudes and the rate of acoustic emission rate were low (Figures 3, 4, and 5). The low level nature of the AE activity in the chalk, which was clearly undergoing ductile deformation with significant plastic strain (Figures 3, 4, and 5), had no locatable AE events under the current testing configuration. As previously noted one of the goals of the research program in Task 7 was to conduct hypocentral location of AE activity during deformation of the chalk. The recorded low level activity, both in the AE rate and amplitudes, calls into question whether this task can be accomplished on such a ductile rock. To clarify these questions the investigators in the research program decided to conduct some limited tests on Berea sandstone and utilize this as an AE reference standard in the research program. Under 1000 psi confining pressure the Berea sandstone initially exhibited: (1) quiet AE activity during initial loading of the sample, (2) increased AE activity at a point on the stress-strain curve halfway to the ultimate strength of the sample, and (3) a higher level of AE activity near failure. Figures 6, 7, and 8 show data from one of the Berea triaxial reference tests for this study (Note: several of these were conducted to ensure reproducibility of the data.) These samples exhibited normal AE activity for a Berea sandstone sample deformed under these conditions. A comparison of the cumulative AE data for Berea and Danian chalk illustrates the vast difference between the behavior of the two rock types. During the Danian chalk test (Figure 5) the deformed sample exhibited only 2300 AE events, even after significant ductile deformation. The Berea sandstone sample showed 130,000 events prior to brittle shear failure (Figure 8). It was decided that, at this stage of the study, it would be more exciting to compare the differences in AE activity for the other rock types obtained for the study including the Indiana limestone, the Oil Creek sandstone, and the Cordoba Cream limestone. A series of experiments comparing the AE activity for each rock type under controlled conditions where all other experimental variables were held constant (e.g., confining pressure) was deemed important to our research program. With this in mind the research team assembled samples of Indiana limestone, Oil Creek sandstone, Cordoba Cream limestone, and additional samples of chalk (the primary rock type of interest) and the Berea sandstone reference sample. The stress-strain curves and the AE rate diagrams for the Indiana limestone are shown in Figures 9 and 10. Interestingly, this rock exhibited a brittle failure at about 10,000 psi differential stress but also had a low level of acoustic emission activity. The cumulative value at termination of the experiment was only 1700 events (Figure 11). This was significantly lower than the Berea sample but in line with the observations of low activity in the Danian chalk sample. The results for the Cordoba Cream limestone are shown in Figures 12, 13, and 14. This rock type deformed ductilely and exhibited only 80 events under conditions comparable to the Berea, Indiana, and Danian chalk samples. The Oil Creek sandstone (Figures 15, 16, and 17) generated the most AE activity of any rock type observed in the test program. At termination of the experiment this high porosity sandstone exhibited 280,000 AE events (nearly double that of the Berea sandstone).

The two sandstones exhibit the highest acoustic emission activities in the study as compared to the limestones and chinks. It is important to note that though the Indiana limestone is stiffer than the Oil Creek sandstone the AE activity of the limestone is significantly lower. This means, significantly, that stiffness and strength are not necessarily indicators as to the activity, intensity, or amplitude of acoustic emission events that will be observed during a deformation experiment. These results suggest that the deformation of calcite and carbonate grains and cements (which dominate the composition of the limestones and chinks) generates a very low level of AE activity as compared to the deformation of the quartz-rich sandstones. It is also important to note that the level of AE activity does not appear to be dependent upon grain size. The Indiana limestone and the Cordoba Cream limestone both exhibit low AE activities as compared to the two sandstones which have equivalent grain sizes.

These preliminary results indicate the acoustic emission activity from the matrix of deforming high porosity limestones and chalks is very difficult to detect. The AE events are infrequent and have a low amplitude as compared to sandstones tested in the experimental program. Analyzing these results within the context of the main premise of the study to image the deformational signatures in reservoir rocks suggests that AE/microseismic imaging of matrix pore collapse and compaction will be difficult to accomplish in the field setting even if ultrasonic detectors are set in place in the reservoir. This may not be true of the sandstones which exhibit more energetic AE activities during the deformation experiments.

In the next quarter of the project the research team will be conducting detailed acoustic velocity testing of these same rock types in an attempt to estimate the poromechanical properties under various deformational pathways. The preliminary results by Scott et al. (1998) on chalk suggest that seismic velocity imaging may be a much more viable technique for monitoring the deformation of oil and gas reservoirs than acoustic emission monitoring.

REFERENCES

- Carlson, S.R. and Young, R.P., 1993. Acoustic emission and ultrasonic velocity study of excavation-induced microcrack damage at the underground research laboratory, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol. 30, No. 7, pp. 901-907.
- Chugh, Y.P. and Heidinger, G.H., 1980. Effect of coal lithology on observed microseismic activity during laboratory tests. *Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures*.
- Dowding, C.H., Samama, L., Shah, S.P., and Labuz, J.F., 1985. Location of acoustic emissions during fracture in slightly anisotropic granite, 26th U.S. Symposium on Rock Mechanics, Rapid City, SD, June 1985.
- Hallbauer, D.K., Wagner, H., and Cook, N.G.W., 1973. Some observations concerning the microscopic and mechanical behavior of quartzite specimens in stiff, triaxial compression. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol. 10, pp. 713-726.
- Khair, A.W. and Hardy, H.R. Jr., 1984. AE monitoring of simulated coal outbursts. *Third Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*.
- Lockner, D. and Byerlee, J.D., 1977. Hydrofracture in weber sandstone at high confining pressure and differential stress. *Journal of Geophysical Research*, Vol. 82, No. 14, pp. 2018-2026.
- Lockner, D. and Byerlee, J., 1978. Development of fracture planes during creep in granite, *Second Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials*.
- Lockner, D.A. Byerlee, J.D., Kuksenko, V., Ponomarev, A., and Sidorin, A., 1991. Quasi-static fault growth and shear fracture energy in granite, *Nature*, Vol. 350, pp. 39-42.
- Lockner, D.A. Walsh, J.B., and Byerlee, J.D., 1977. Changes in seismic velocity and attenuation during deformation of granite. *Journal of Geophysical Research*, Vol. 82, No. 33, pp. 5374-5378.
- Nishizawa, O., Kusunose, K., Satoh, T., and Takahashi, M., 1990. Positive feedback fracture process induced by nonuniform high-pressure water flow in dilatant granite. *Journal of Geophysical Research*, Vol. 95, No. B13, pp. 21583-21592.
- Nishizawa, O., Onai, K., and Kusunose, K., 1985. Hypocenter distribution and focal mechanism of AE events during two stress stage creep Yugawara andesite. *Pageoph.*, Vol. 122, pp. 36-52.
- Rutledge, J.T., Fairbanks, T.D., Albright, J.N., Boade, R.R., Dangerfield, J., and Landa, G.H., 1994. Reservoir induced seismicity at the Ekofisk oil field. *Eurock '94*, pp. 589-595.
- Scholz, C.H., 1968. Microfracturing and the inelastic deformation of rock in compression. *J. Geophys. Res.*, Vol. 73, pp. 1417-1432.

- Scott, T.E., Azeemuddin, M., Zaman, M., and Roegiers, J.-C., 1998b. Stress-induced variations in acoustic velocities in chalk. *Proceedings, 3rd North American Rock Mechanics Symposium*, Cancún, Mexico.
- Scott, T.E., Ma, Q., and Roegiers, J.-C., 1993. Acoustic velocity changes during shear-induced compaction of sandstone, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol. 30, No. 6, pp.763-769.
- Sondergeld, C.H. and Estey, L.H., 1981. Acoustic emission study of microfracturing during the cyclic loading of westerly granite. *Journal of Geophysical Research*, Vol. 86, No. B4, pp. 2915-2924.
- Spetzler, H. and Mizutani, H., 1986. Comment on "Localization of dilatancy in Ohshimi granite under constant uniaxial stress." *Journal of Geophysical Research*, Vol. 91, No. B6, pp. 6565-6566.
- Spetzler, H.A., Sobolev, G.A., Sondergeld, C.H., Salov, B.G., Getting, I.C., and Koltsov, A., 1981. Surface deformation, crack formation, and acoustic velocity changes in pyrophyllite under polyaxial loading. *Journal of Geophysical Research*, Vol. 86, No. B2, pp. 1070-1080.
- Yanigadani, T., Ehara, S., Nishizawa, O., Kusunose, K., and Terada, M., 1985. Localization of dilatancy in Ohshima granite under constant uniaxial stress. *Journal of Geophysical Research*, Vol. 90, No. B8, pp. 6840-6858.
- Zang, A., Wagner, C.F., and Dresen, G., 1996. Acoustic emission, microstructure, and damage model of dry and wet sandstone stressed to failure. *Journal of Geophysical Research*, Vol. 101, No. B8, pp. 17507-17521.

LIST OF ACRONYMS AND ABBREVIATIONS

AE	=	Acoustic Emission
GAIS	=	Geomechanical Acoustic Imaging System
OU	=	The University of Oklahoma
RMI	=	Rock Mechanics Institute at the University of Oklahoma
SIRT	=	Simultaneous Iterative Reconstruction Technique
SWF	=	Shallow Water Flows
VHF	=	Very High Frequency
V_p	=	Compressional Wave Velocity
V_s	=	Shear wave velocity
V_p/V_s	=	Ratio of compressional wave velocity to the shear wave velocity

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 fourth quarter targets highlighted

Fig.1. Schematic of the acoustic emission systems in the Keck Geomechanical Acoustic Imaging System.

Fig.2. Schematic of the acoustic emission feedback system .

Fig.3. Stress-strain diagram for Danian chalk.

Fig.4. AE rate diagram for Danian chalk.

Fig.5. Cumulative AE for Danian chalk.

Fig.6. Stress-strain diagram for Berea sandstone AE reference.

Fig.7. AE rate diagram for Berea sandstone AE reference.

Fig.8. Cumulative AE for Berea sandstone AE reference.

Fig.9. Stress-strain diagram for Indiana limestone.

Fig.10. AE rate diagram for Indiana limestone.

Fig.11. Cumulative AE for Indiana limestone.

Fig.12. Stress-strain diagram for Cordoba Cream limestone.

Fig.13. AE rate diagram for Cordoba Cream limestone.

Fig.14. Cumulative AE for Cordoba Cream limestone.

Fig.15. Stress-strain diagram for Oil Creek sandstone.

Fig.16. AE rate diagram for Oil Creek sandstone.

Fig.17. Cumulative AE for Oil Creek sandstone.