Acoustical Imaging and Mechanical Properties of Soft Rock and Marine Sediments

(Technical Progress Report #15302R02)

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ABSTRACT

Mechanically weak formations, such as chalks, high porosity sandstones, and marine sediments, pose significant problems for oil and gas operators. Problems such as compaction, subsidence, and loss of permeability can affect reservoir production operations. For example, the unexpected subsidence of the Ekofisk chalk in the North Sea required over one billion dollars to re-engineer production facilities to account for created during that compaction (Sulak 1991). Another problem in weak formations is that of shallow water flows (SWF). Deep water drilling operations sometimes encounter cases where the marine sediments, at shallow depths just below the seafloor, begin to uncontrollably flow up and around the drill pipe. SWF problems created a loss of $150 million for the Ursa development project in the U.S. Gulf Coast SWF (Furlow 1998a,b; 1999a,b). The goal of this project is to provide a database on both the rock mechanical properties and the geophysical properties of weak rocks and sediments. These could be used by oil and gas companies to detect, evaluate, and alleviate potential production and drilling problems. The results will be useful in, for example, pre-drill detection of events such as SWF's by allowing a correlation of seismic data (such as hazard surveys) to rock mechanical properties. The data sets could also be useful for 4-D monitoring of the compaction and subsidence of an existing reservoir and imaging the zones of damage.

During the second quarter of the project the research team has: (1) completed acoustic sensor construction, (2) conducted reconnaissance tests to map the deformational behaviors of the various rocks, (3) developed a sample assembly for the measurement of dynamic elastic and poroelastic parameters during triaxial testing, and (4) conducted a detailed review of the scientific literature and compiled a bibliography of that review. During the first quarter of the project the research team acquired several rock types for testing including: (a) Danian chalk, (b) Cordoba Cream limestone, (c) Indiana limestone, (d) Ekofisk chalk, (e) Oil Creek sandstone, (f) unconsolidated Oil Creek sand, and (g) unconsolidated Brazos river sand. During the second quarter experiments were begun on these rock types. A series of reconnaissance experiments have been carried out on all but the Ekofisk (for which there is a preliminary data set already inhouse). A series of triaxial tests have been conducted on the Danian chalk, the Cordoba Cream limestone, the Indiana limestone, and sand samples to make a preliminary determination of the deformational mechanisms present in these samples.

TABLE OF CONTENTS

LIST OF GRAPHICAL MATERIALS FOR THE PROJECT

INTRODUCTION

Changes in the mechanical behavior of rock or soil when subjected to a stress perturbation will be accompanied by significant changes in their acoustic compressional and shear wave velocities. Rock formations can undergo deformation via a wide range of mechanisms such as elasticity, plasticity, dilatancy, pore collapse, and consolidation. If these deformational mechanisms can be matched to specific compressional and shear wave velocity signatures then engineers, geologists, and geophysicists may be able to use 2D, 3D, and 4D seismic surveying techniques to image reservoir rock damage or to detect rocks and sediments that have the potential to be damaged during drilling or production operations. One of the most important steps in developing such surveying techniques is to obtain a set of data containing both acoustic and deformational properties of rocks that traditionally resulted in reservoir damage. This quarterly report concerns the reconnaissance experiments to outline the deformation of a wide range of rocks as preparation for the detailed acoustic emission, acoustic tomography, and dynamic tensor experiments to come later in the study.

In addition to imaging potential damage zones, the same data may provide detailed information on the mechanical moduli of the damaged (or undamaged) rocks. Currently, the research team is working on utilizing the same data to image the poromechanical properties of the damaged rock as well.

EXECUTIVE SUMMARY

A series of reconnaissance triaxial tests have been conducted on various types of rock to outline the deformational behaviors in preparation for the more detailed experiments to be conducted later in the project. Suites of experiments have been conducted on limestones, chalks, and sand samples. Preliminary failure maps which indicate the brittle-ductile transition have been created. The results indicate that the brittle-ductile transition for: (1) the Danian chalk is around 1000 psi confining pressure, (2) the Cordoba Cream limestone is approximately 1200 psi, and (3) the Indiana limestone is around 5000 psi. Previous work on the Ekofisk chalk indicated that the brittle-ductile transition occurs at around 1000 psi.

During the past three months of the project the investigators have developed and tested a new sample assembly so that these anisotropic elastic parameters could be measured later in Task 8. Past experimental techniques required acquiring velocity data on three separate, oriented plugs to generate the dynamic elastic moduli for inherent anisotropy in rock samples (King 1970; Lo et al. 1986). However, this approach does not allow an investigation into cases where deformation (i.e. triaxial stress states) causes the rock or sediment to fail. At the present time no laboratory data on the stress-induced anisotropic dynamic moduli has ever been produced. The new sample configuration will allow the acquisition of this important data under different types of stress paths. The configuration consists of an array of axial and lateral compressional and shear wave sensors mounted on either the surface of the core sample or in steel load platens. The new configuration also allows acquisition of compressional waves oriented at 45^{o} to the principal load axis.

During this second quarter the research team also developed a theoretical basis for obtaining poromechanical parameters from the acoustic wave data to be obtained later this year (in Task 8). To date, no known data have been obtained on anisotropic poromechanics parameters. A new method will utilize the acoustically derived stiffness components to calculate the anisotropic Biot's effective stress parameters: α_{33}, and α_{11}.

Also, during this quarter a detailed bibliography was compiled reviewing selected topics important to the research team. These include reviewing past research on the following topics: (1) laboratory techniques previously used in this type of project, (2) rock and soil deformational mechanisms, and (3) other aligned topics that are salient to the project. The laboratory techniques include examining methods and applications of acoustic velocity measurements, acoustic emission, ultrasonic tomography, anisotropic velocity measurements, shear wave bender elements, and dynamic elastic moduli measurements. A collection of papers has also been created for various deformational mechanisms that are being encountered in the experimental testing program. These include: dilatancy, elasticity/poroelasticity, compressibility, and pore collapse/compaction. Pertinent publications have also been searched out for the following topics: shallow water flows, acoustic velocities in marine sediments, liquefaction, and induced seismicity in petroleum reservoirs. Several hundred papers have been compiled, by subject heading, by the research team. A bibliography is attached in Appendix 1.

EXPERIMENTAL

The second quarter of this project encompassed three tasks as outlined on the project timeline (see Table 1). These include:

Task 4: Prepare sandstone and chalk samples
Task 5: Constructing lateral acoustic emission and acoustic velocity sensors
Task 6: Reconnaissance tests on chalk and limestone samples

In addition to accomplishing the above tasks researchers: (1) have completed a bibliography of scientific research related to specific topics in the project, and (2) have worked out some of the theoretical details for the determination of some of the poroelastic rock parameters from the dynamic acoustic data which will be obtained later this year (Task 8).

Task 4: Prepare Sandstone and Chalk Samples

The samples were prepared as right circular cylinders. The Danian chalk, Cordoba Cream limestone, and Indiana limestone were cut with the traditional diamond core barrel and then the ends were trimmed and surface ground plane parallel to within .0005 inch tolerance. The Oil Creek samples and Antlers sand are being cut with custom made hand twist core barrel because of their extremely friable nature. This coring technique was developed for this project and core barrels of several sizes have been constructed. The sand samples are molded into the encapsulating jacket at the time of sample preparation. For Task 6 most of the samples prepared for testing were 1-inch diameter plugs with lengths of 2-inches. The sand samples are larger (2.125-inch in diameter and 4.25-inch in length).

Task 5: Constructing Lateral Acoustic Emission and Acoustic Velocity Sensors

A series of lateral acoustic sensors have been fabricated. A similar design has been successfully used by Scott et al. (1993) in previous research. Two different types of lateral sensors have been made for this research project. They include: (1) single element acoustic emission sensors, and (2) three component sensors with one compressional and two orthogonally mounted shear wave elements. Details of these sensors were presented in the first quarterly report. Both types of sensors have been constructed and are now in use in the laboratory.

Task 6: Reconnaissance Tests on Chalks

During the first quarter of this project researchers obtained six different blocks of rock and two unconsolidated sand samples to be tested in the experimental program: (1) Danian outcrop chalk, (2) Cordoba Cream (Austin) limestone, (3) Indiana limestone, (4) Ekofisk chalk, (5) Oil Creek sandstone, (6) Antlers sandstone, (7) unconsolidated Oil Creek sand, and (8) unconsolidated Brazos River sand.

Reconnaissance experiments have been conducted on the Danian chalk, the Indiana limestone, and the Cordoba Cream limestone. Tests are in progress on the sandstone and sand samples at this time. The purpose of the reconnaissance experiments is to: (1) define the Mohr failure envelope for these materials, (2) define the pore collapse and compactive yield surface of the material so that the deformational mechanisms can be discerned, and (3) determine the suitability of the rock or sand samples for subsequent, more detailed (and more expensive) ultrasonic tomography and acoustic emission experiments. Cylindrical core samples having a 1 inch diameter and a 2-inch length were used in all these preliminary experiments. The use of small samples is important in that only a fraction of the available rock is tested so that the majority of the core material can be preserved for the detailed acoustic experiments that will require larger samples.

Danian chalk. This is a clean, white outcrop chalk obtained from Denmark. It has a porosity of 35% and is equilivalent in strength and character to the Ekofisk chalk in the North Sea. The Ekofisk chalk represents a reservoir that has undergone severe subsidence and compaction (over 30 feet) in the last 30 years. The Danian chalk samples will be used in experiments to simulate this process. The reconnaissance tests have been conducted and are presented in Figure 1. The Mohr envelope indicates an internal friction angle of 23.5^{o}, and a cohesion (C_o) of 440 psi. Brazilian tests indicate that the tensile strength (T_o) of this rock is about 50 psi. The failure envelope exhibits a linear nature (Figure 1). Triaxial tests have been conducted at confining pressures of 0, 200, 400, 500, 700, 1000, 1250, 1500, 2000, and 3000 psi. The yield points for both brittle and ductile behaviors are plotted in Figure 2. The cap surface for the onset of pore collapse (and ductility) starts at a confining pressure 1000 psi and extends to about 3000 psi. This Danian chalk exhibits very similar deformational behavior to the Ekofisk chalk the research team has previously tested (Scott et al. 1998b).

Cordoba Cream limestone. This rock is a buff colored Austin chalk quarried in Texas. It has a lower porosity (25%) than either the Danian or Ekofisk chalk rocks. Triaxial tests have been conducted at confining pressures of 0, 200, 300, 500, 1000, and 1500 psi. Initial experiments on this rock type have been rather disappointing (see Figure 3) as the data appears to yield an inconsistent trend for the failure envelope. This does not seem to be the case with the other rock types tested in this program to date. The difference in strengths is thought to be due to the inhomogeneous nature of the porosity distribution (in some cases it exhibits a visibly vuggy type porosity) relative to the scale of the small sample size selected for these reconnaisance experiments. Researchers are in the process of testing larger core samples to determine if this rock type will yield useful results for the later acoustic velocity/ acoustic emission experiments. They are also investigating whether the intact material exhibits significant acoustic inhomogeneity or anisotropy. If this determination is made then another block will be selected from the RMI rock sample storage for use in this program. The tensile strength (T_o) of this chalk was found to be 644 psi. Pore collapse and ductility start just above 1200 psi (Figure 4).

Ekofisk chalk. The Ekofisk chalk is buff colored, high porosity (35%), highly fractured limestone from the North Sea. Researchers in the Rock Mechanics Institute (RMI) have retained a few samples of the Ekofisk reservoir from a previous study (Scott et al. 1998b) and these samples will be tested in the current research program. Since there is a limited amount of this reservoir rock, researchers have decided to preserve it for the detailed acoustic velocity tests later in the research program (Task 8 at the end of this year). The previous work by Scott et al. (1998b) indicated that the brittle-ductile transition occurred at around 700-1000 psi and extends to 3000 psi.

Indiana limestone. A block of Indiana limestone (porosity 18.1%) was also obtained for the research program. Experiments were conducted at confining pressures of 0, 100, 250, 500, 1000, 2000, and 5000 psi. The Mohr failure envelope is curved concave downward (see Figure 5). In this case the Mohr envelope was fitted with two lines, one at low normal stresses and one at high normal stresses (with internal friction angles of 16.5^o and 53^o, respectively). The Indiana limestone has a measured tensile strength (T_o) of 643 psi. The transition to ductile behavior occurs just above 5000 psi (Figure 6).

The research team is currently in the process of conducting reconnaissance experiments on the sandstones and sands selected for the research project. These include the Antler sandstone, a weakly cemented, poorly consolidated sandstone that has a porosity of approximately 37% , the Oil Creek sandstone, a very clean quartz arenite with a porosity averaging around 33-35%, and the unconsolidated Oil Creek sand and the Brazos River sand. Preliminary data has been acquired primarily using polyolefin jackets. All of these materials will have very low strengths and so at this time considerable attention is being given to determining the added experimental error (if any) induced by the selection of the external jacketing material for the core sample. Teflon, polyolefin, latex, and buna jacketing materials are currently being tested on unconsolidated Oil Creek sands to determine if these will alter the strength or the nature of the deformation during the experiment.

These preliminary deformation maps are useful in selecting the pressure/stress conditions for subsequent tomography, acoustic emission location, and dynamic tensor experiments. For example, the data on the Danian chalk (Figure 1) indicates that a triaxial test at 500 psi confining pressure exhibits brittle shear failure. However, to examine acoustic velocities or acoustic emission during ductility (and therefore compaction) the experiment should be conducted at a confining pressure between 1000 and 3000 psi. Likewise, the design of a uniaxial strain experiment (to simulate a reservoir deformational pathway) should start at a confining pressure greater than 1000 psi. The research team is in the process of analyzing these deformation diagrams to plan the experimental matrix for the later tomography, acoustic emission, and dynamic tensor experiments. This test plan will be presented in the next quarterly report.

Investigation into Dynamic Elastic/Poroelastic Parameters

Task 8, which will be conducted during the last half of this year, involves using acoustic wave propagation to measure the dynamic elastic moduli in a transversely isotropic rock during the deformation experiments. However, some exploratory work needs to be conducted during this second quarter of the project to prepare for that later task. To this end, a new sample assembly has been developed to facilitate acquisition of the acoustic waveform data. Second, a preliminary theoretical basis for the determination of poromechanical moduli from these dynamic data sets has also been developed in the project.

The new sample assembly

A new sample assembly has been developed for acquisition of dynamic elastic/poroelastic moduli. In previous research, experiments required three separate samples to determine the properties of a transversely isotoropic rock (e.g., King 1970, Lo et al. 1986) . Figure 7 provides an illustration of this technique and Figure 8 shows the corresponding calculations. This technique has limitations in that it can only be used to examine inherent anisotropy (i.e., sedimentary layering or fracturing) in samples during hydrostatic (equal) stress states. It cannot be used to examine anisotropy induced by differential stresses and it is problematic in that three different, separate samples are required (i.e., homogeneity problems may arise).

The new sample assembly, which has already been tested in the Rock Mechanics Institute laboratory, acquires multiple oriented compressional and shear acoustic raypaths in cylindrical core samples subjected to high pressures. For a transversely isotropic rock only five raypaths are actually required. These include: the axial compressional wave (Vp_{33}), the lateral compressional wave (Vp_{11}), the shear wave polarized in the plane of symmetry (Vs_{12}), the shear wave polarized along the axis of symmetry (Vs_{31}), and a compressional wave along a raypath oriented at 45^o to the axis of symmetry (see Figures 9 and 10). Even though only five raypaths are required the sample assembly was developed and will be used, while 15 raypaths are acquired (see Figure 10). Such a large number of raypaths will be obtained to assist in documenting that the samples exhibit transverse isotropy, are homogeneous acoustically, and create some redundancy in case of transducer failure. Figure 10 shows an illustration of the orientation of the raypaths in vertical and horizontal sections through a cylindrical sample.

Anisotropic poroelastic data from acoustic data sets

The research team also decided to use some time to develop a preliminary theoretical basis for measuring poroelastic parameters from the dynamic data set which will be obtained in Task 8. Elastic anisotropy in rocks is well documented in the scientific literature. The theory for the determination of the five independent elastic stiffness constants from acoustic wave propagation has been established. King (1970), and Lo et al., (1986) illustrate examples of the application of this technique. This method uses compressional and shear wave velocities to determine the components of the stiffness matrix of a transversely isotropic rock. As a result, many experimental studies have examined these elastic stiffness constants in a variety of inherently transversely isotropic rocks and used them to derive the elastic parameters. In the new sample assembly constructed at the RMI, two Young's moduli (see Figure 11), three Poisson's ratios (see Figure 12), and two shear moduli (see Figure 13) can be determined for a given rock. These data are important for both the engineering purposes (for examining problems such as borehole stability or reservoir deformation) and for geophysics application to seismic wave propagation and exploration.

Whereas the determination of dynamic elastic moduli from laboratory acoustic wave experiments is well documented there are no equivalent methods to allow determination of the poroelastic parameters. These include: Biots effective stress parameter (α), Skempton's coefficient (B), and the Biot's modulus (M). For an isotropic rock there are two independent elastic parameters and two independent poroelastic parameters. For a transversely isotropic rock, however, there are 5 independent elastic parameters and 3 independent poroelastic parameters (Abousleiman et al. 2000). A theory for the anisotropic poroelastic parameters has been developed by Abousleiman and Cui (1998) and is based on the assumption that the microisotropy exists at the rock grain level. The poroelastic parameter, α,. is important in determining the effective stress states of rocks. The determination of α is important in a wide variety of engineering problems ranging from borehole stability to reservoir compaction. The determination of α is generally accomplished by either of two laboratory methods: the direct and indirect methods. The indirect method involves measuring the bulk modulus of the solid grains (K_s) during a drained unjacketed hydrostatic test, and the bulk modulus of the rock grain framework (K) during a drained jacketed test. The Biot's parameter can then be calculated $\alpha = 1 -(K/K_s)$. The direct method involves measuring the changes in fluid volume to changes in the total rock volume (Abousleiman and Chhlajlani 1994). Both methods are static methods and no known way has yet been derived to allow determination of the dynamic Biot's parameter during acoustic experiments. One method proposed by the petroleum wireline log industry is to determine the dynamic Young's modulus and Poisson's ratio and then calculate the dynamic bulk moduli from that. However, this method is based on the assumption that the rock is isotropic and homogeneous and it would be improper to use this method for rocks with either inherent transverse isotropy (i.e., shale layering) or stress-induced anisotropy. Anisotropy in Biot's effective stress parameters (α_1 and α_3) has been demonstrated theoretically to have a marked effect on many engineering problems and its determination has been given some importance within the petroleum industry. Attempts have been made to generate these by biaxially loading cores with bedding planes oriented at various angles. Such approaches have severe problems due to the superposition of a biaxial stress field on oriented anisotropic rocks. The new approach can acquire these data on cylindrical samples (see Figure 14).

A key breakthrough in determining the dynamic poroelastic moduli from acoustic rock properties stemmed from a theoretical investigation of anisotropy in poroelasticity by Abousleiman and Cui (1998, 2000). Their theory generated a method for calculating the two Biots parameters from the elastic stiffness constants :

$$\alpha_1 = 1-((C_{11}+C_{12}+C_{13})/3K_s)$$

$$\alpha_3 = 1-((2C_{13}+C_{33})/3K_s).$$

Since the stiffness constants (i.e., the C_{ij}'s) in anisotropic rocks can be accomplished via the laboratory measurements of acoustic compressional and shear wave propagation described by King (1970), this provides a method for the determination of anisotropic Biot's parameters in a transversely isotropic rock. An independent measurement of K_s, in conjunction with the measurement of the five stiffness constants in a tranversely isotropic rock, will therefore allow determination of both anisotropic Biots parameters.

A brief abstract of this concept was submitted and presented at the 2001 Spring Meeting of the American Geophysical Union in Boston, Massachussetts. Full research papers are under preparation on this aspect of the research program for submission to peer reviewed journals (in the third quarter of this project) and more details will be provided in the next DOE quarterly report.

Research Bibliography for the Project

A detailed review of the scientific literature has been compiled by the faculty researchers and graduate research assistants. At the third quarter of the project the principal investigators will begin to draft a series of scientific papers for publication in peer reviewed journals. This bibliography is designed to provide a foundation for that step. This project is truly multidisciplinary and it reflects diverse fields in both engineering and earth science with research topics involving rock physics, rock mechanics, soil mechanics, and geophysics. As such the literature survey reflects that multidisciplinary nature. The topics, at this time, are grouped into three main categories with sub-topics listed below:

1. Laboratory techniques and technologies to be used in the research project

- (1.1) Acoustic velocities (determined by the time of flight method)
- (1.2) Acoustic emission/acoustic emission hypocentral location
- (1.3) Ultrasonic tomography
- (1.4) Anisotropic acoustic velocity
- (1.5) Shear wave bender element measurement techniques
- (1.6) Dynamic tensor measurements

2. Research topics on the deformational mechanisms of rocks and soils

    - (2.1) Dilatancy
    - (2.2) Elasticity/poroelasticity
    - (2.3) Compressibility
    - (2.4) Pore collapse/compaction

3. Other papers important to the research program (primarily field related problems)

    - (3.1) Shallow water flows
    - (3.2) Acoustic velocities in marine sediments
    - (3.3) Liquefaction
    - (3.4) Induced seismicity in petroleum reservoirs

The laboratory technology list addresses only those techniques which will be used over the life of the project. A literature search was also conducted on the liquefaction of soils as it seems to be a similar mechanism (descriptively) for the problem of shallow water flows created during drilling in the deep water marine environment.

These references will be useful for the literature review for the research papers to be prepared in the next quarter of the project. The only other literature survey will be made in the second year of the project and will include: (1) 3D, 4D, and 3C Seismic Imaging (2) velocity anisotropy (field cases), and (3) shallow water seismic (hazard) surveys. These will be important in developing correlations between the laboratory research and field practice.

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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 timeline with second quarter targets highlighted

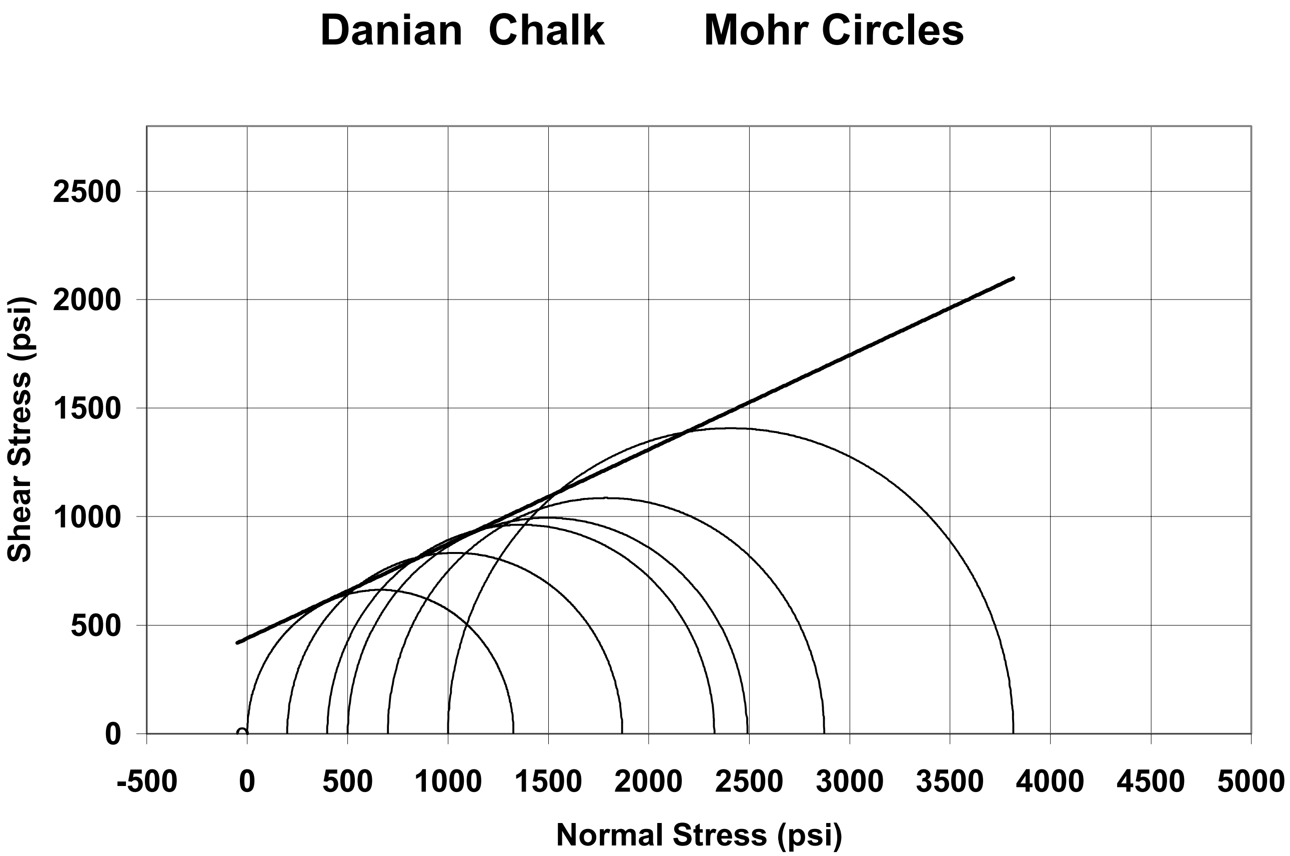


Fig.1. The Mohr failure envelope for the Danian Chalk reconnaissance experiments.

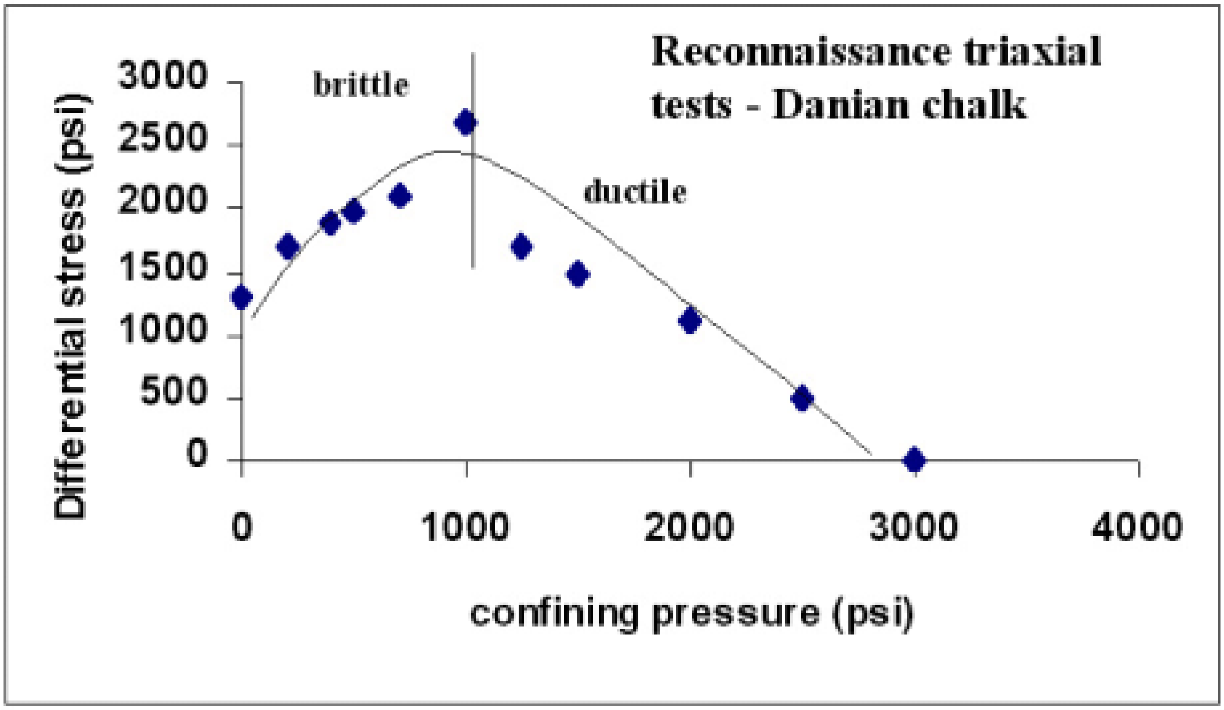


Fig.2. A differential stress-confining pressure plot for Danian chalk.

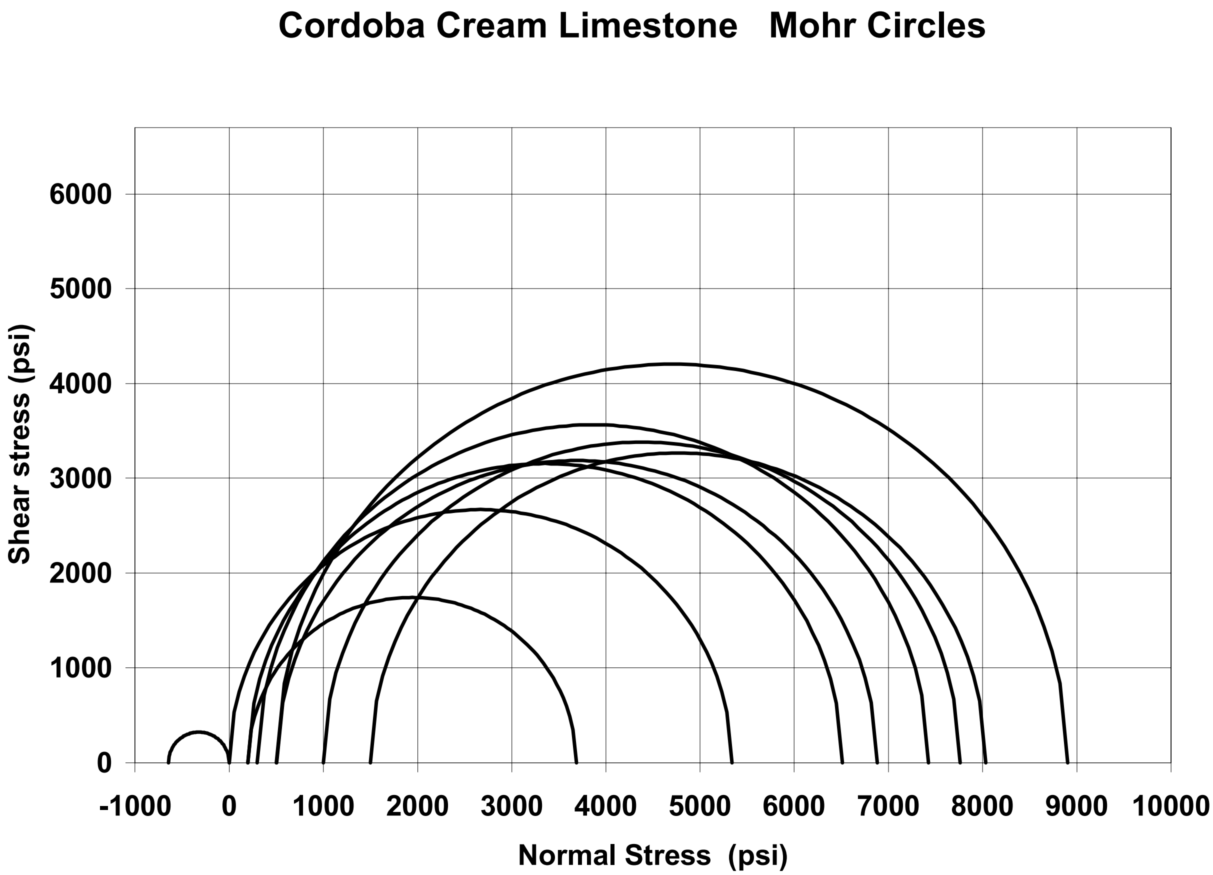


Fig.3. The Mohr failure circles for the Cordoba Cream limestone experiments.

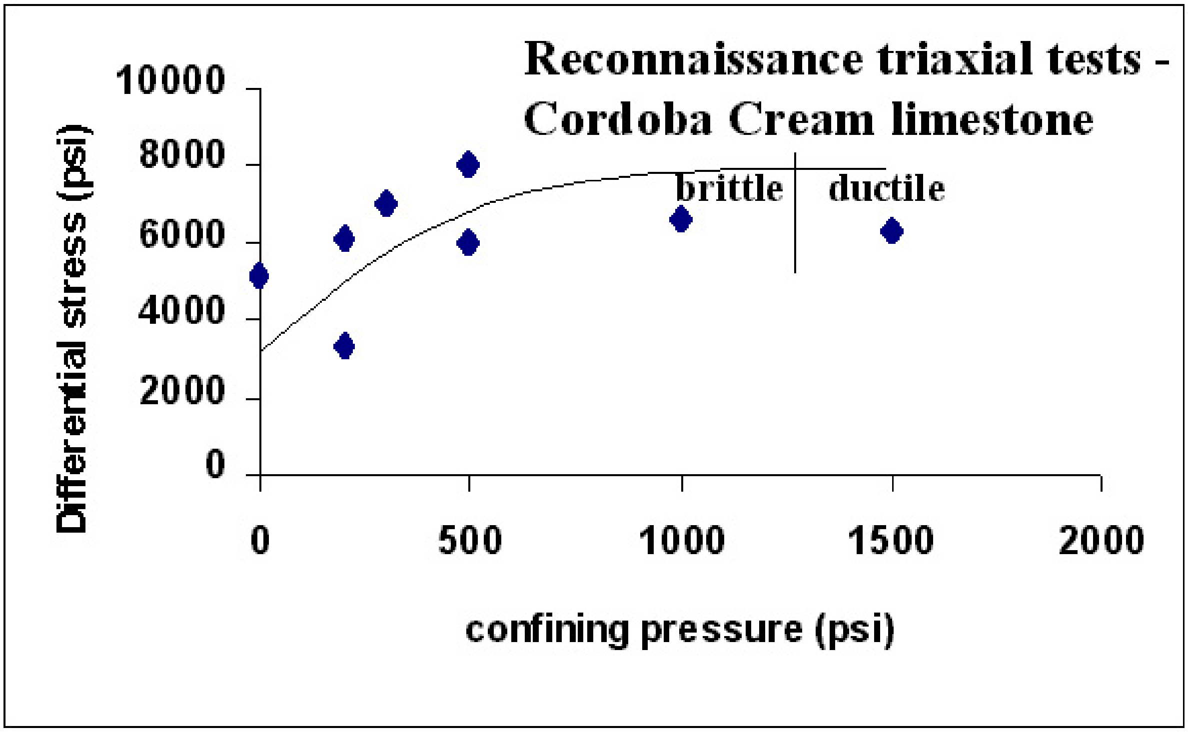


Fig.4. A differential stress-confining pressure plot for Cordoba Cream limestone.

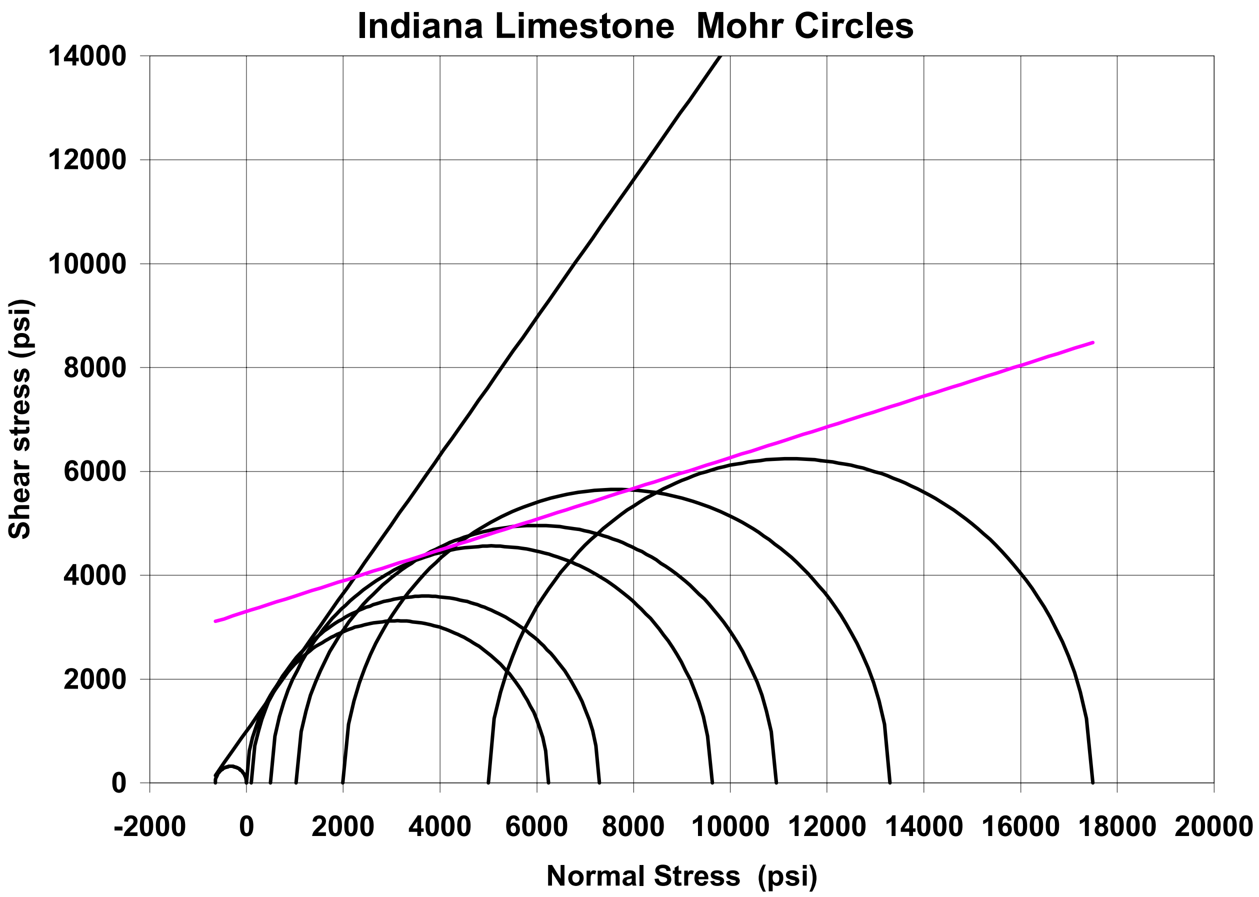


Fig.5. The Mohr failure envelope for the Indiana limestone experiments.

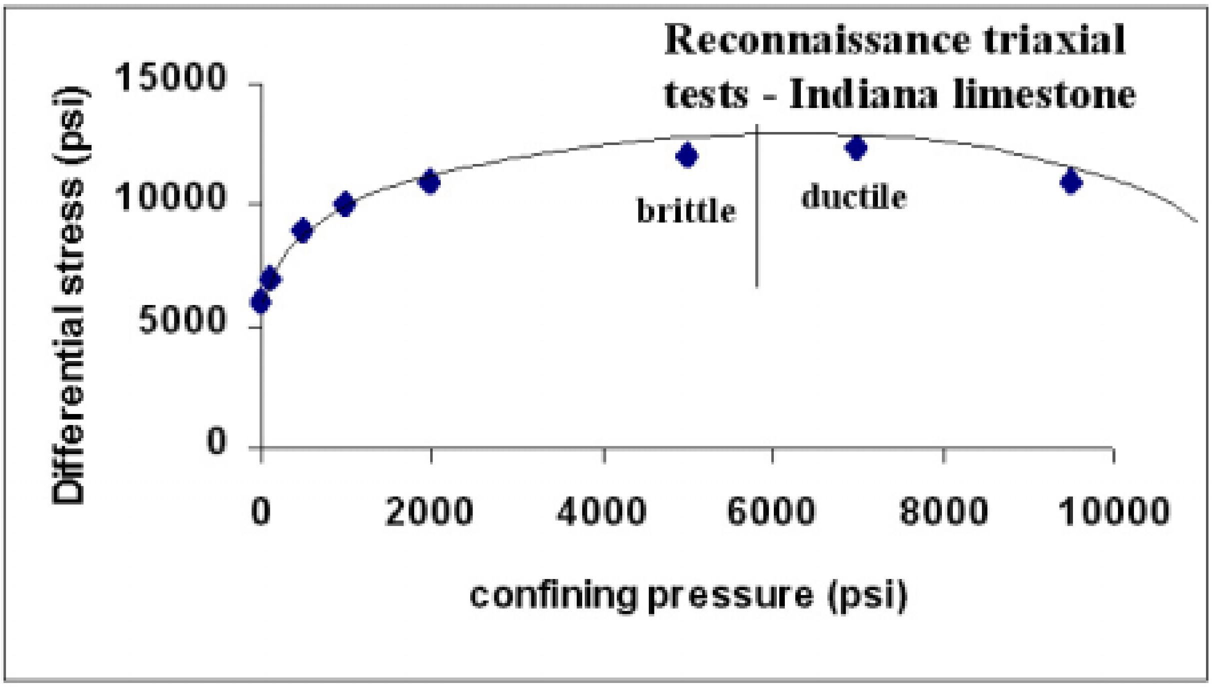


Fig.6. A differential stress-confining pressure plot for Indiana Limestone.

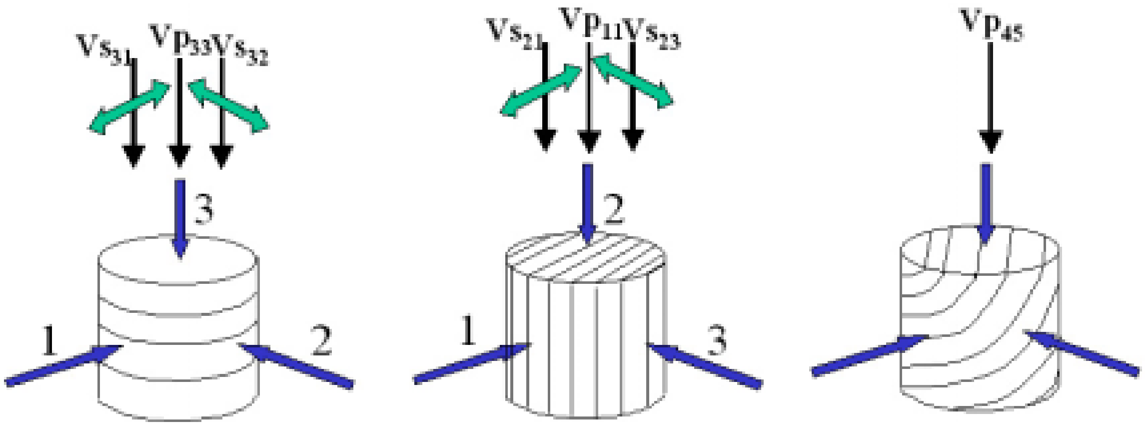


Fig.7. A schematic of the traditional three core method (see Lo et al. 1986) for the acquisition of dynamic elastic moduli for a transversely isotropic rock.

$$\sigma_i = C_{ij}\, \varepsilon_i$$

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{13} \\ \tau_{23} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{bmatrix}$$

Five independent stiffness coefficients are present: C_{11}, C_{12}, C_{13}, C_{33}, and C_{55}. (C_{44} is a function of C_{11} and C_{12}).

The five independent stiffness components can be determined from the velocities via:

$$C_{11} = \rho Vp^2{}_{11}$$

$$C_{12} = C_{11} - 2\rho Vs^2_{23}$$

$$C_{33} = \rho Vp^2_{33}$$

$$C_{44} = \rho Vs^2_{13}$$

e.g., King (1970); Lo et al. (1986)

$$C_{55} = C_{11} - C_{12}$$

$$C_{13} = -C_{44} + \sqrt{4\rho Vp^4_{45} - 2\rho Vp^2_{45}(C_{11} + C_{33} + 2C_{44} + + (C_{11} + C_{44})(C_{33} + C_{44})}$$

Fig.8. The stiffness matrix and stiffness component calculations from compressional and shear wave velocities.

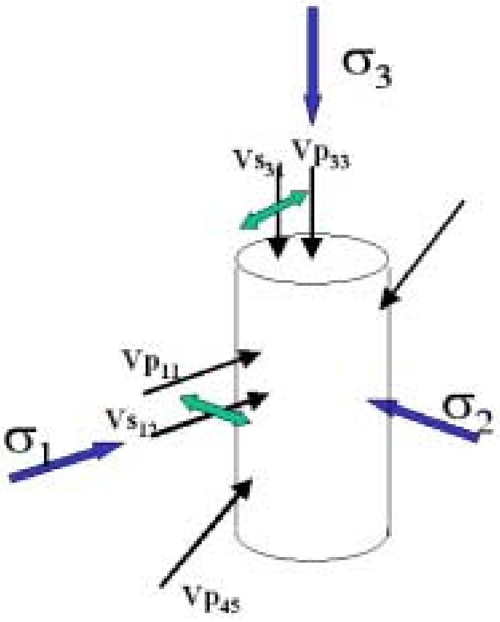


Fig.9a.The minimum five raypaths necessary to determine the anisotropic elastic moduli.

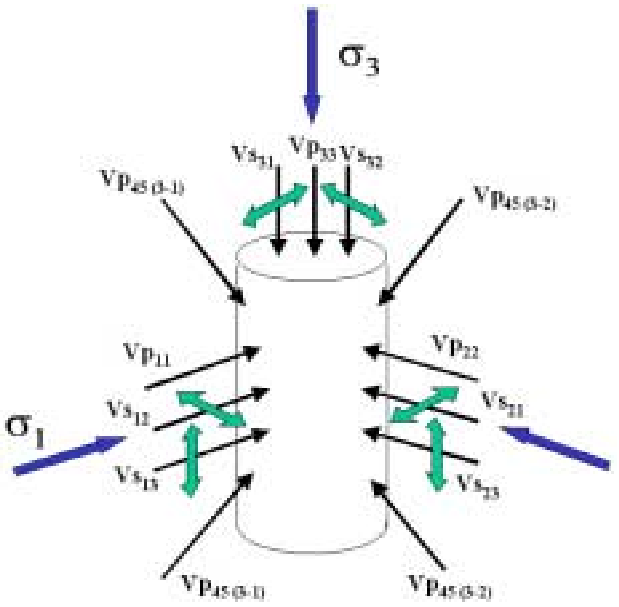


Fig.9b. A schematic of the raypaths in the new cylindrical sample assembly for the acquisition of dynamic elastic moduli for a transversely isotropic rock.

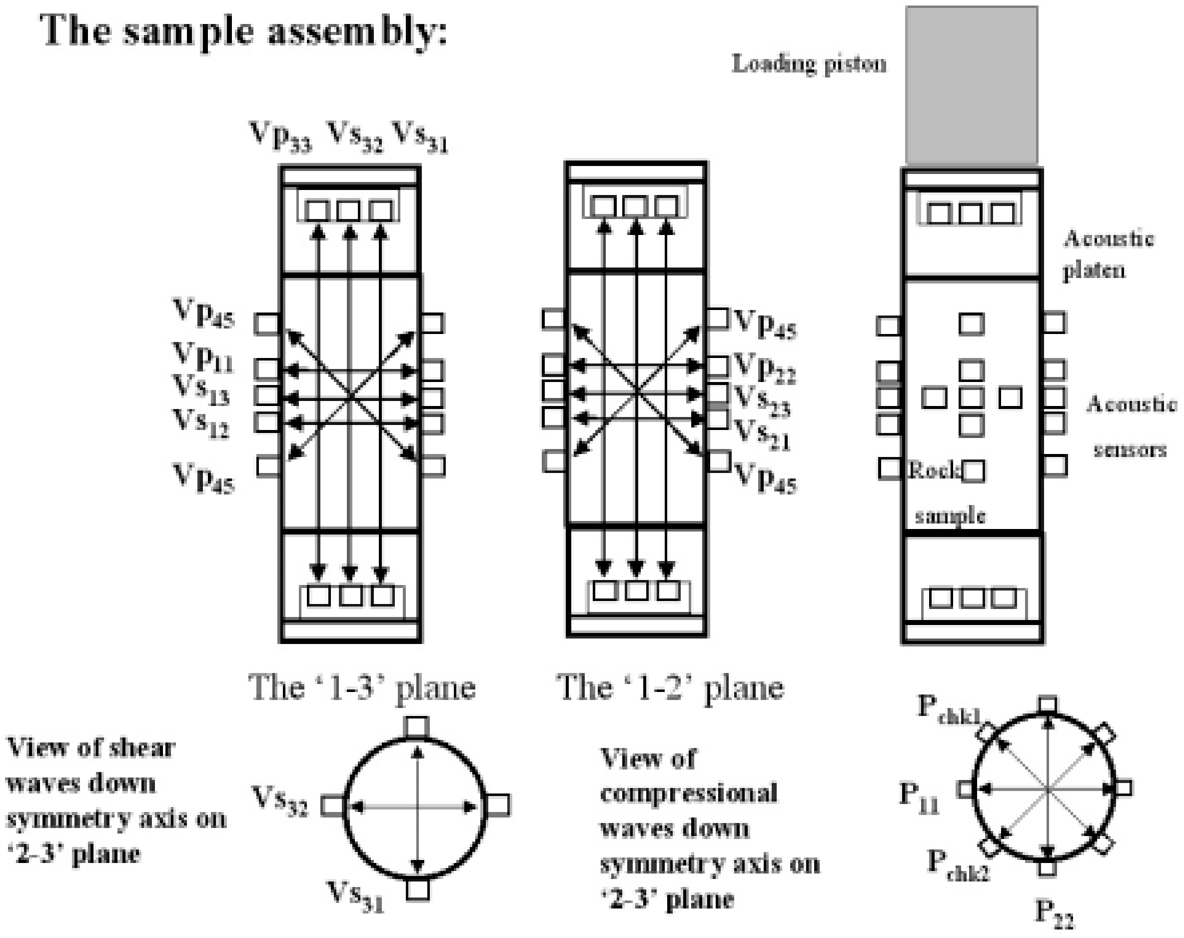


Fig.10. A sectional diagram of the new sample assembly for use in a triaxial cell.

$$E_{33} = \frac{D}{C_{11}^2 - C_{12}^2}$$

$$E_{11} = \frac{D}{C_{11}C_{33} - C_{13}^2}$$

Where D is the determinant of:

$$D = \begin{vmatrix} C_{11} & C_{12} & C_{13} \\ C_{12} & C_{11} & C_{13} \\ C_{13} & C_{13} & C_{33} \end{vmatrix}$$

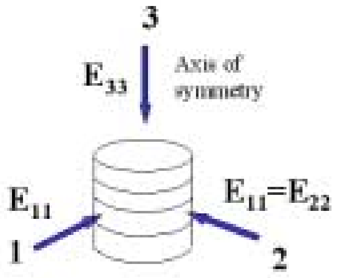


Fig. 11 The determination of dynamic Young’s moduli from acoustic data in a transversely isotropic cylindrical sample (equations from King (1970)).

$$\nu_{12} = \frac{C_{12}C_{33} - C_{13}^2}{C_{11}C_{33} - C_{13}^2}$$

$$\nu_{13} = \frac{C_{13}\,(C_{33} - C_{13})}{C_{11}C_{33} - C_{13}^2}$$

$$\nu_{31} = \frac{C_{13}}{C_{11} + C_{12}}$$

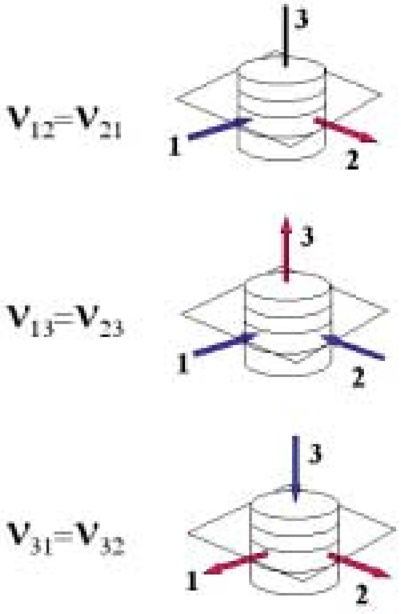
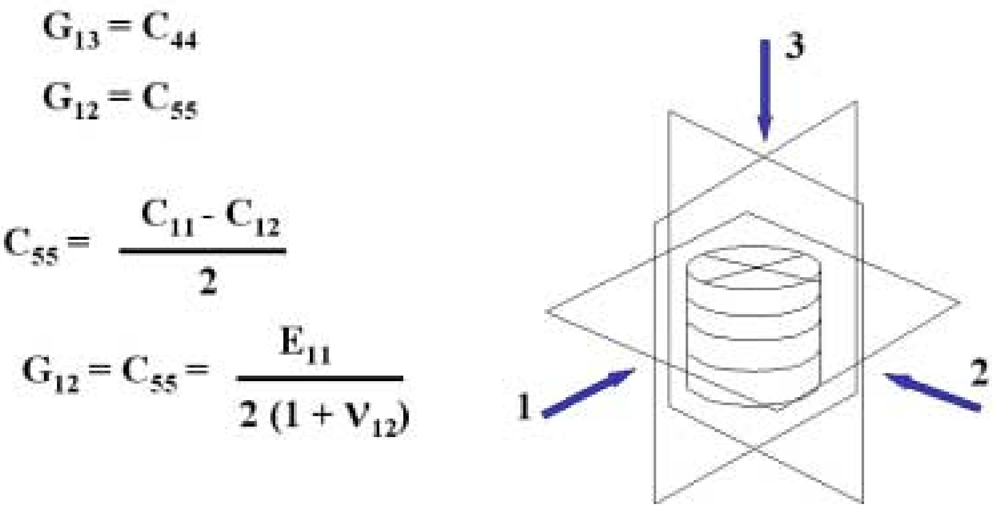


Fig.12 The determination of dynamic Poisson’s ratios from acoustic data in a transversely isotropic cylindrical sample (equations from King (1970)).



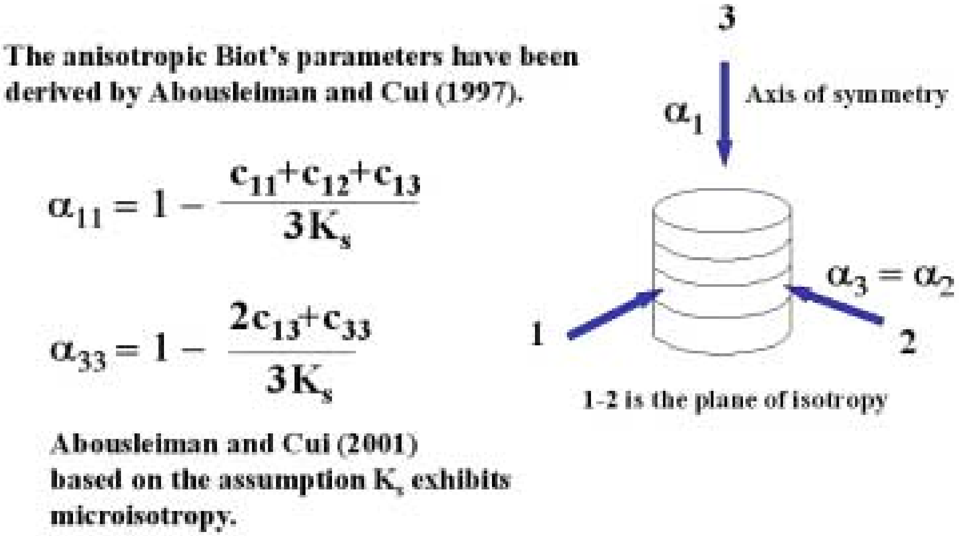
$$G_{13} = C_{44}$$

$$G_{12} = C_{55}$$

$$C_{55} = \frac{C_{11} - C_{12}}{2}$$

$$G_{12} = C_{55} = \frac{E_{11}}{2\,(1 + \nu_{12})}$$

Fig.13. The determination of dynamic shear moduli from acoustic data in a transversely isotropic cylindrical sample.



The anisotropic Biot's parameters have been derived by Abousleiman and Cui (1997).

$$\alpha_{11} = 1 - \frac{c_{11}+c_{12}+c_{13}}{3K_s}$$

$$\alpha_{33} = 1 - \frac{2c_{13}+c_{33}}{3K_s}$$

Abousleiman and Cui (2001) based on the assumption K_s exhibits microisotropy.

Fig.14. The determination of dynamic Biot's parameters from acoustic data in a transversely isotropic cylindrical sample.

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