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MATERIAL PROPERTIES OF DEVONIAN SHALE FOR STIMULATION TECHNOLOGY DEVELOPMENT

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Executive Summary

A major component of the Eastern Gas Shales Project being conducted by the Morgantown Energy Technology Center involves the development and evaluation of new and refined stimulation techniques which might be suitable for stimulating Devonian shale wells. As part of the EGSP stimulation development program, both quasi-static hydraulic-type stimulation treatments and dynamic stimulation techniques employing combinations of explosives and/or propellants are being evaluated. Evaluation of these techniques is being accomplished through a combination of numerical simulations, laboratory experiments and full-scale field tests. The numerical simulation or modeling efforts require that the relevant physical properties of Devonian shale be adequately defined. For the quasi-static, hydraulic-type treatments shale fracture characteristics and elastic properties are critical parameters which must be quantitatively described. For the dynamic-type treatments shale yielding characteristics must be known as well as the fracture and elastic properties. As the great majority of data for these properties has been obtained from quasi-static experiments, it will be desirable and in some cases critical to know the degree to which rate effects may modify the statically determined parameters. In an attempt to provide a consistent and self-contained data base on the physical properties of Devonian shale, Science Applications has reviewed and collected previously generated data from numerous sources and has performed additional experiments so as to define the applicability of some of the quasi-static data to the evaluation of dynamic treatments.

The review, experiments and evaluation which have been conducted on Devonian shale physical properties have resulted in the following principle conclusions:

- The elastic properties and yield surfaces defined by triaxial tests on Devonian shale may be significantly dependent upon shale type and organic richness, but a more systematic approach to core selection and testing will be required to establish correlations.

- Sufficient material property data for modeling and stimulation design exist only on a very site-specific basis, and more testing is required for identifying generic and regional trends.
- Dynamic experiments employing modified split-Hopkinson-bar techniques were so controlled by anisotropic sample failure that quantitative data on dynamic yield strength could not by obtained.
- There is a strong need for the development of experimental techniques and the generation of concordant data on the dynamic yield characteristics of Devonian shale at strain rates representative of explosive and tailored-pulse-loading.

MATERIAL PROPERTIES OF DEVONIAN SHALE
FOR STIMULATION TECHNOLOGY DEVELOPMENT

Introduction

The ultimate objective of the Eastern Gas Shales Project (EGSP) is to increase production from Devonian shales by improving methods of exploration and development. To appreciate the need for material property data in this program, one should look first at the nature of Devonian shale production, then at the specific goals that have been established for improving this production, and finally at the role that material property data play in achieving these goals.

Despite estimates of large quantities of gas in place (some as high as 1450 Tcf), actual production from Devonian shales has been marginal due to the unconventional nature of the reservoir. Most of the gas in place is absorbed in the shale matrix. Production of this gas depends on the existence of a natural fracture system and on linking this system to the wellbore. When the pressure in the reservoir is reduced, the gas diffuses through the shale into the fracture system. Another factor that complicates production efforts are the low reservoir pressures. Initial reservoir pressures of 1.5 to 3.5 MPa (200 to 500 psi) are common in wells 900 to 1200 meters (3,000 to 4,000 feet) deep, where the normal hydrostatic head would be 9 to 12 MPa (1300 to 1700 psi).

Specific goals in the EGSP are to improve techniques of resource characterization and reservoir stimulation. In that part of the program devoted to resource characterization, efforts are being made to correlate potentially productive intervals with material properties that are detectable from cores and logs. In conventional reservoirs one looks for porosity or shows of hydrocarbons, but in the Devonian shales traditional indicators can be misleading or non-existent. Porosity is not a good basis for making estimates of productivity because as mentioned above most of the gas is in the shale matrix and permeability is controlled by natural fractures which are not detected by conventional porosity logs. In order to get measurable gas shows, the wellbore must intersect the fracture system: however, fracture spacing may be such that the well is drilled through the reservoir without actually intersecting it. Over 80% of the wells with no measurable initial flow become commercial after stimulation by wellbore shooting links the hole to the fracture system. Obviously the location of natural fracture systems will be controlled in large part by the tectonic environment, but the intensity of fracturing should be a function of the mechanical properties of the rock as well. What is needed is a method of identifying zones that are likely to be fractured without the fractures necessarily intersecting the wellbore. If some correlation can be found between fracture intensity and certain mechanical properties, such as tensile strength, elasticity, or relative ductility, this would aid in selecting candidate zones for completion and stimulation.

Research efforts in stimulation technology are directed toward minimizing formation damage associated with both hydraulic and dynamic stimulation techniques. Damage associated with dynamic techniques is mostly mechanical, and so a knowledge of material properties plays a direct role in improving these techniques. The mechanical damage is either the result of plugging channels of flow by excessive amounts of fine material produced by intense fracturing near the wellbore or closing channels of flow by yielding and/or compacting the material around the wellbore. Numerical codes are being used to evaluate different dynamic techniques, and they require specific material property data as input. Required properties, such as elastic constants, tensile strength, yield envelope, and compaction curves, can directly affect the results of these numerical evaluations. Damage associated with hydraulic techniques is usually the result of a chemical reaction between the fracturing fluid and the formation. In some cases the fluid weakens or dissolves the cementing materials in the formation causing the release of fines which plug channels of flow. Weakening of the formation can also result in proppant embedment which would lower fracture flow capacity. Where clays are present the fluid can cause them to swell and plug permeability. To minimize these types of damage, low-residual-fluid treatments such as foam fracs are being tested. Material properties play only an indirect role in improving these techniques. Material properties are used in the design of hydraulic fracturing treatments to establish a relation between the volume of fluid used in a job and the expected extent of the fracture. In Devonian shales this is important in determining the volume of fluid necessary to intersect the natural fracture system.

The objectives of this report are to bring together as much material property data on Devonian shales as possible so as to form a data base for the analyses and evaluations discussed above and to point out areas where additional data are needed. Existing data are either based on static tests usually run at a strain rate of $10^{-4}s^{-1}$ or on dynamic tests run at strain rates greater than $10^{4}s^{-1}$. Since several of the dynamic stimulation techniques being considered produce strain rates in the neighborhood of $10^{2}s^{-1}$, SAI has undertaken the task of measuring the mechanical properties of Devonian shales at intermediate strain rates with a split-Hopkinson-bar (SHB) apparatus.

Extent and Character of Devonian Shales

The gas-bearing Devonian shales underly major portions of the Appalachian, Illinois, and Michigan basins and can be quite heterogeneous in both composition and properties. The stratigraphy varies considerably within a given basin, but in general the rock is composed of grey shale interbedded with organic-rich brown and black shale sequences and occasional silty or sandy layers. The Devonian as a whole tends to be thicker in the east where deltaic wedges interfinger with the shales. The brown and black shales occur more frequently in the central and western portions of the Appalachian Basin and in the Illinois Basin and represent an organic mud facies that accumulated on the western side of an epicontinental sea. Another characteristic contributing to the heterogeneity of the shale is the natural fracture system which varies in intensity both laterally and stratigraphically. The natural fracture system can have a strong effect on the properties of the shale and should be taken into consideration in evaluating and applying the data given below.

State of Stress in Devonian Shales

Material properties, both physical and mechanical, are known to vary with the state of stress, and some, such as permeability and strength, can be particularly sensitive to changes in the state of stress. Unfortunately the state of stress in the Earth's crust is one of the more difficult geologic parameters to measure. It is usually expressed in terms of the magnitude and orientation of the three principal stresses. In areas that are not undergoing active tectonic deformation (sometimes refered to as "tectonically relaxed"), the mutually perpendicular principal stresses are usually assumed to be perpendicular and parallel to the horizontal, which makes the vertical principal stress equal to the overburden. Using the well-known formula for overburden stress;

$$\sigma_v = \rho g h$$

where

ρ = density
g = acceleration due to gravity
h = depth of burial

and an average density of 2.6 gm/cm^3 for Devonian shales, (see Table 1) one obtains a vertical stress gradient of 25.5 kPa/m (1.13 psi/ft).

Theoretically the horizontal principal stresses can be determined from pressure measurements made during hydraulic fracturing treatments, if the created fracture is vertical. Hydraulic fractures tend to propagate perpendicular to the least principal stress, and it is reasoned that the pressure required to hold the fracture open is equal to the least principal stress. During a treatment as fluid is being pumped the pressure measured at the surface includes pressure due to friction in the pipe, perforations, and fracture. When pumping stops the friction pressure goes to zero. The pressure measured at this time, while the fracture is supposedly still open, is called the instantaneous shut-in pressure (ISIP). When the ISIP is added to the hydraulic head in the wellbore, a bottom hole pressure is obtained which should be equal to the pressure in the fracture. This bottom hole pressure divided by the depth of the zone being treated is called fracture gradient and is taken as a measure of the minimum horizontal in situ stress, assuming the fracture is vertical. If the fracture gradient is equal to or greater than the overburden gradient, then it is likely that a horizontal fracture has been created. In this case the overburden stress would be the least principal stress.

A wide range of fracture gradients have been reported for Devonian shales. McKetta[1] collected 67 measurements from Kentucky, West Virginia, and Ohio. The maximum was 23.8 kPa/m (1.05 psi/ft), and the minimum was 5.0 kPa/m (0.22 psi/ft) with an average of about 11 kPa/m (0.5 psi/ft). The lower values are less than a hydrostatic head, which is 9.8 kPa/m (0.433 psi/ft), so that these formations could not support a wellbore full of water. Three fracture gradients measured in the Devonian shales of Gallia, Ohio, are 12.2 kPa/m (0.541 psi/ft), 14.0 kPa/m (0.619 psi/ft), and 17.2 kPa/m (0.760 psi/ft).[2] A value of 19.5 kPa/m (0.860 psi/ft) was measured by Terra Tek for the upper grey shale of the Huron in Lincoln County, West Virginia.[3] Calculated in situ horizontal stress gradients for six lower zones in the same well ranged from 10.8 kPa/m (0.475 psi/ft) to 17.9 kPa/m (0.793 psi/ft) with an average of 15.1 kPa/m (0.665 psi/ft). The calculated stresses in the organic rich brown shales were consistently lower than in the grey shale

Table 1. Physical properties of Devonian shales.

Source	Locality	Bulk Density (gm/cm³)	Porosity (%) Open	Porosity (%) Closed	Porosity (%) Total	Permeability (μd) Gas	Permeability (μd) Liquid
Kalyoncu, et al.[6]	Lincoln Co., WV	2.68 ± 0.09 (17)	0.86 ± 0.68	1.90 ± 1.70	3.06 ± 1.93	0.0 to 0.7	
	Christian Co., KY	2.48 ± 0.14 (13)	0.59 ± 0.34	1.16 ± 1.41	1.75 ± 1.34		
	Sullivan Co., IN	2.48 ± 0.11 (11)	1.53 ± 1.32	1.79 ± 1.67	4.02 ± 2.32		
	Washington Co., OH	2.68 ± 0.06 (25)	0.88 ± 0.47	1.43 ± 1.85	2.31 ± 1.89		
Kalyoncu, et al.[7]	Allegany Co., NY	2.62 ± 0.06 (165)			5.45 ± 4.43	0.0	
Hanson, et al.[8]	Lincoln Co., WV						
	brown gaseous (1047m)	2.51 ± 0.01 (5)					
	white slate (1131m)	2.69 ± 0.01 (3)					
	Marcellus black(1216m)	2.49 ± 0.00 (3)					
Harvey, et al.[9]	Sangamon Co., IL	2.41 ± 0.06 (20)					
	Christian Co., KY	2.48 ± 0.14 (13)					
Cremean et al.[10]	Lincoln Co., WV	2.3 to 2.8	1.0		4.0	5.0	0.01
Jones, et al.[11]	Lincoln Co., WV						
	upper grey (908m)	2.57 ± 0.06 (9)			4.69 ± 2.69 (3)		
	middle brown(1050m)	2.48 ± 0.02 (9)			4.96 ± 1.90 (3)	4.7±3.4(3)	
	lower grey (1146,65m)	2.66 ± 0.01 (10)			7.42 ± 1.94 (3)	<0.1	
	lower brown (1218m)	2.68 ± 0.01 (9)			3.60 ± 2.72 (3)	15	

units. The range of all the fracture gradients given above is similar to the range for other regions, but the Devonian shales tend to have more low values than other regions.

The maximum horizontal principal stress is more difficult to determine because it requires a knowledge of the *in situ* tensile strength of the rock, which is difficult to measure, and an accurate measure of the breakdown pressure during a fracturing treatment. Uncertainties are introduced in the breakdown pressure by the fact that the pumps are running, and so there is some friction pressure, and also by the fact that the formation may have already been broken down in the process of drilling and completing the well. Nevertheless Terra Tek has attempted to measure the maximum horizontal principal stress from the breakdown pressure in Columbia Gas well #20403 in Lincoln County, West Virginia.[4] Two methods of calculating the stress from the breakdown pressure were used, one using a simple tensile strength for the rock and the other employing fracture mechanics theory. The first gave a stress of 38.1 MPa, or a gradient of 45.5 kPa/m, and the second gave 30.3 MPa or a gradient of 36.2 kPa/m. This was the maximum principal stress in this case where the overburden was 22.1 MPa and the minimum horizontal principal stress was 16.3 MPa.

The orientation of the principal stresses can vary locally, particularly near faults or in areas of intense folding, but there seems to be fairly good agreement about the regional orientation of the stresses in the Appalachian Basin. There is a general east-west trend to the orientation of the maximum principal stress except in the Rome Trough of western West Virginia where the trend is N 45^o - 50^o E.[5] This orientation is supported by impression packer measurements of fracture orientation made in well #20403, in Lincoln County, West Virginia, which is on the edge of the Rome Trough.

Physical Properties

Measurements of bulk density, porosity, and permeability have been made on Devonian shale core from several wells in the Appalachian and Illinois basins. The primary reasons for making these measurements has been to look for correlations between these properties and gas production, but the data are also used in reservoir modeling, mechanical modeling, and stimulation design. A summary of data from various localities is presented in Table 1. In general, bulk densities range from about 2.3 to 2.8 gm/cm^3, but most are between 2.5 and 2.7 gm/cm^3. Total porosities range from almost 0 to 7%, and permeabilities from almost 0 to 15μd. In such an overview, often some of the important trends are masked, and in this case one such trend is a correlation between density and organic content.[6] Densities have been found to be inversely proportioned to organic content and seem to be a better indicator of possible production than the more traditional properties like porosity and permeability.

The study by Kalyonca et al.[6] (Table 1) shows one of the reasons why porosity is a poor indicator of production. In core from four states the average closed porosity was greater than the average open porosity in each case. This is also reflected in the gas permeabilities which in most cases were nearly zero.

Static Mechanical Properties

Elastic Constants. Static elastic constants have been measured by Terra Tek under confining pressure on core from Columbia Gas well #20403, in Lincoln County, West Virginia.[11] Table 2 presents Young's moduli and Poisson's ratios measured in compression and extension tests for four different zones. All tests were run on cylinders oriented parallel to the bedding plane. The confining pressures were chosen to correspond to the overburden stress at the depth from which the cores were taken. They were based on a gradient of 22.6 kPa/m (1 psi/ft); however given the density of the rock (see Table 1, Jones et al.[11]) a gradient of 25.5 kPa/m (1.13 psi/ft) would have been more appropriate for the overburden stress. The reason for running different rocks at different confining pressures was to simulate in situ conditions so that the data could be used in the interpretation of logs.

For purposes of comparison, the data on Young's modulus are plotted in Figure 1. The values are consistently higher in compression than they are in extension, which may be due to the higher mean stress in compression. There also appears to be some tendency for Young's modulus to be higher at higher confining pressures, but it is difficult to draw any conclusions about this since the rock type is varying with

Table 2. Elastic constants for Well #20403, Lincoln County, West Virginia.

Stratigraphic Unit	Depth (m)	Confining Pressure (MPa)	Young's Modulus (GPa)		Poisson's Ratio	
			Compression	Extension	Compression	Extension
Upper Grey Shale*	909	20.6	29.5 ±3.6	21.7 ±1.7	0.21 ±0.09	0.17 ±0.09
Middle Brown Shale	1050	23.8	33.0 ±2.8	24.8 ±2.5	0.20 ±0.03	0.18 ±0.03
Lower Grey Shale	1165	26.4	33.8 ±11.4	20.7 ±1.0	0.25 ±0.09	0.20 ±0.03
Lower Brown Shale	1218	27.6	55.2 ±3.5	24.8 ±2.8	0.37 ±0.08	0.20 ±0.00

*Referred to as upper brown shale in Terra Tek report,[11] probably in error.

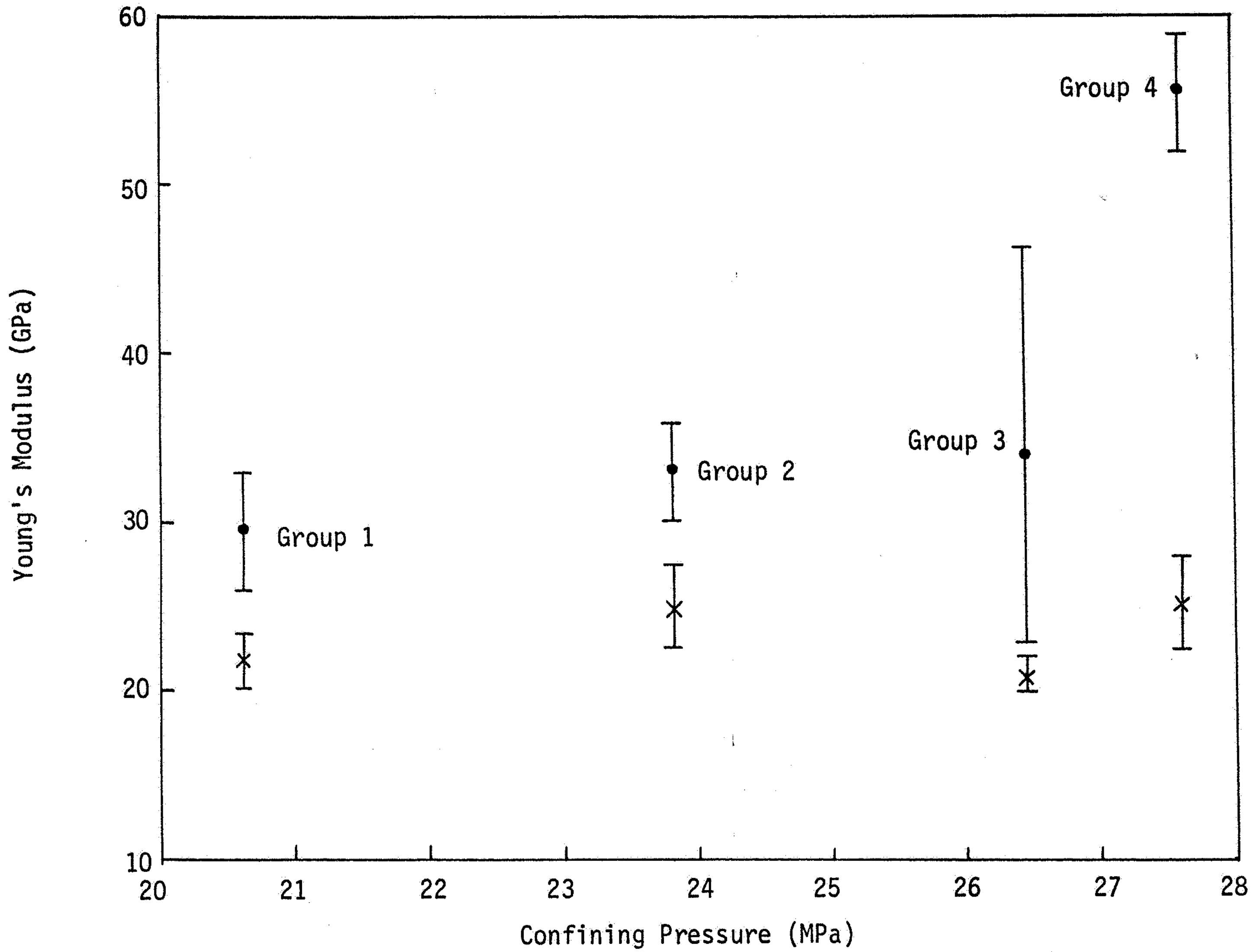

Figure 1. Means and standard deviations for Young's moduli of different Devonian shales at different confining pressures tested in compression (●) and extension (x).

each set of data. If more general use is to be made of the data, the effects of lithology and confining pressure need to be separated.

The only other source for elastic constants found in this search is a study by Cremean, et al.[10] of three wells in Lincoln County, West Virginia. Values for elastic constants from this paper are presented in Table 3, and can be seen to compare favorably with the data generated by Terra Tek.

Tensile Strength. Tensile strengths have been measured on core from two wells, one the same Columbia Gas Well #20403 in Lincoln County, West Virginia, as discussed above and the other in Christian County, Kentucky. Table 4 gives tensile strengths for the New Albany Shale from Christian County based on Brazil tests.[12] Tensile strength was measured at different orientations with the tensile stress parallel to the bedding plane, and there appears to be a slight but consistent variation of strength with orientation. Brazil tests were also run on core from well #20403 by Lawrence Livermore Laboratory (LLL).[8,13] For the purposes of their study, which also includes compression tests presented in the next section, LLL divided the core into four units as shown in Table 5. The corresponding unit name used by Terra Tek is also given. The tests were run with the tensile stress oriented both parallel and perpendicular to the bedding planes, and, as can be seen in Table 6, the rock was consistently weaker when the tension was perpendicular to the bedding.

Compressive Strength. Compressive strengths have been measured on core from Mason County, West Virginia,[14] as well as the core from Lincoln County, West Virginia mentioned above. The data in Table 7 show a definite tendency for the core from Mason County to be stronger when compressed perpendicular to bedding. The values of compressive strength given seem low compared to both the tensile strengths given above (compressive strengths are usually 8 to 12 times higher than tensile strengths) and the unconfined compressive strengths for the core from Lincoln County given in Tables 8 - 15.

The yield envelopes presented in Figures 2 - 7 are based on the results of the compression tests on the Lincoln County, West Virginia core

Table 3. Elastic constants for Devonian shale, Lincoln County, West Virginia.

CONSTANT	RANGE
Young's Modulus	23.9 GPa to 44.3 GPa
Poisson's Ratio	0.122 to 0.239
Bulk Modulus	13.7 GPa to 23.9 GPa
Shear Modulus	9.9 GPa to 19.7 GPa

Table 4. Tensile strength of New Albany Shale, Christian County, Kentucky.

Orientation	Number of Samples	Average Tensile Strength (MPa)
-60^{0}	16	7.52
-30^{0}	12	7.28
0^{0}	14	8.04
30^{0}	9	8.19
60^{0}	14	8.34
90^{0}	11	8.43

Table 5. Stratigraphic nomenclature used by LLL and Terra Tek for core from Columbia Gas Well #20403, Lincoln County, West Virginia.

Group No.	Depth (m)	LLL Unit	Terra Tek Unit
1	807-1039	upper grey shale	upper grey shale*
2	1039-1116	brown gaseous shale	middle brown shale
3	1116-1203	white slate	lower grey shale
4	1203-1233	Marcellus black shale	lower brown shale

*Referred to as upper brown shale in Terra Tek report,[11] probably in error.

Table 6. Tensile strength of Devonian shale, well #20403, Lincoln County, West Virginia.

Group	Depth (m)	Mean Tensile Strength ± Std. Dev.(no.tests) Parallel	Perpendicular
1	945	2.47 ± 0.53(10	
1	856	4.07 ± 1.30(10)	
1	898	4.65 ± 1.13(5)	2.52 ± 0.23(12)
2	1066, 1089	6.24 ± 0.72(9)	2.78 ± 0.56(9)
3	1134	5.10 ± 0.99(10)	2.46 ± 0.53(8)
4	1212, 1210	4.83 ± 1.83(10)	1.91 ± 0.26(10)

Table 7. Uniaxial compressive strength of Devonian shale, Mason County, West Virginia.

Orientation with respect to bedding	Compressive Strength (MPa)
⊥	12.52
⊥	16.17
⊥	15.14
⊥	9.31
∥	3.00
∥	3.97

Table 8. Group 1, 856 m, perpendicular to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	39.4	13.23	brittle
0.1	97.2	32.50	brittle
0.1	149.4	49.90	brittle
50	326.3	158.77	brittle
100	457.7	252.57	brittle
150	567.2	339.07	brittle
200	593.5	397.83	brittle
300	727.1	542.37	brittle

Table 9. Group 1, 898 m, parallel to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	46.5	15.60	brittle
0.1	115.1	38.47	brittle
0.1	75.8	25.37	brittle
50	226.7	125.57	brittle
100	342.7	214.23	brittle
150	333.9	261.30	brittle
200	377.4	325.80	brittle
300	450.3	450.10	brittle

Table 10. Group 2, 1066 m, perpendicular to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	102.6	34.30	brittle
0.1	115.9	38.73	brittle
50	206.2	118.73	brittle
100	260.6	186.87	brittle
150	319.8	256.60	brittle
200	304.4	301.47	transitional
250	317.8	355.93	ductile

Table 11. Group 2, 1046 m, parallel to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	58.8	19.7	brittle
0.1	55.8	18.7	brittle
50	215.0	121.67	brittle
100	250.0	183.33	brittle
150	290.0	246.67	brittle
200	380.3	326.77	brittle
200	382.1	327.37	brittle
250	355.3	368.43	transitional
300	374.5	424.83	ductile

Table 12. Group 3, 1131-m depth, perpendicular to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	60.3	20.20	brittle
0.1	42.1	140.80	brittle
50	116.9	88.97	brittle
100	160.8	153.60	brittle
150	139.0	194.33	brittle
150	139.0	196.33	brittle
200	171.9	257.30	transitional
250	165.5	305.17	ductile
300	200.7	366.90	ductile

Table 13. Group 3, 1134-m depth, parallel to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	21.0	7.10	brittle
0.1	31.9	10.73	brittle
50	73.1	74.37	brittle
100	101.5	133.83	brittle
150	124.0	191.33	brittle
250	161.6	303.87	brittle
300	181.3	360.43	brittle

Table 14. Group 4, 1204- and 1212-m depths, perpendicular to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	95.0	31.77	brittle
0.1	110.3	36.87	brittle
0.1	81.4	27.23	brittle
50	159.6	103.20	brittle
100	214.5	171.50	brittle
150	249.5	236.50	transitional
200	271.1	290.37	ductile
300	349.0	416.33	ductile

Table 15. Group 4, 1204- and 1210-m depths, parallel to bedding, stress values in MPa.

Confining Pressure	Differential Stress	Mean Stress	Behavior
0.1	69.7	23.33	brittle
0.1	57.4	19.23	brittle
50	177.8	109.27	brittle
100	241.7	180.57	brittle
150	286.0	245.33	brittle
200	333.9	311.30	brittle
300	438.7	446.23	brittle

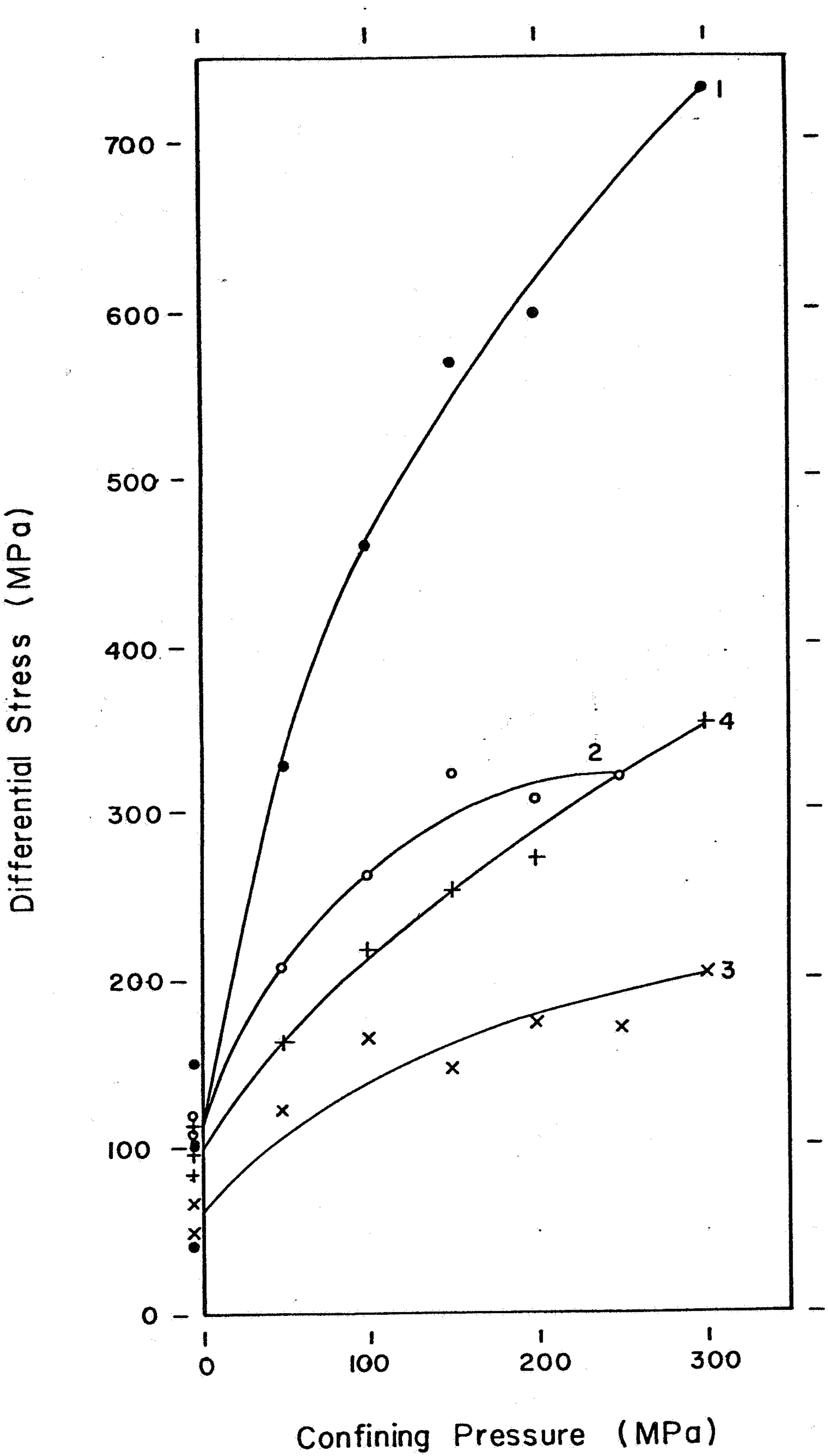

Figure 2. Yield envelopes for grey upper shale (1), brown gaseous shale (2), white slate (3), and Marcellus black shale (4) loaded perpendicular to bedding.

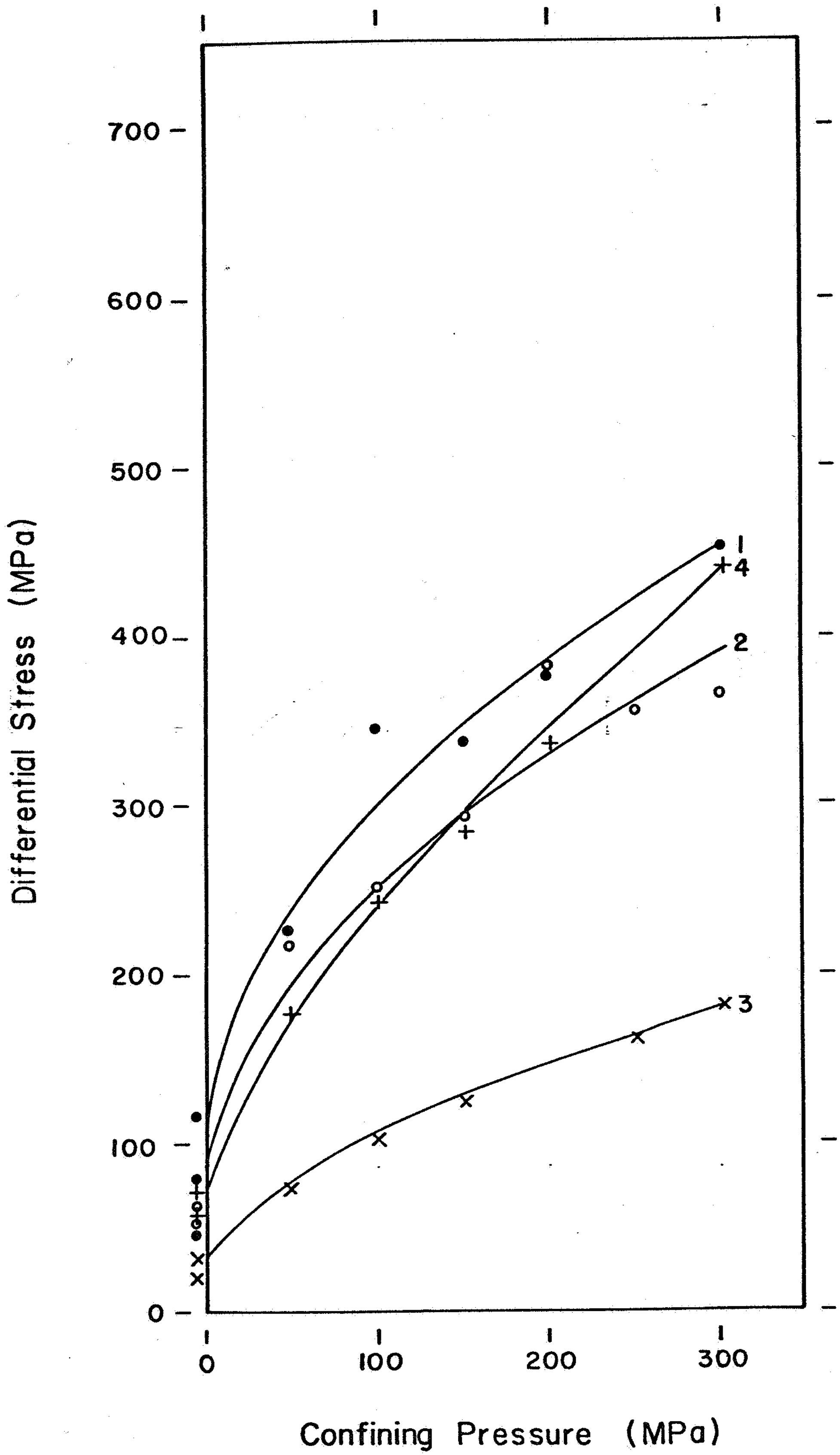

Figure 3. Yield envelopes for grey upper shale (1), brown gaseous shale (2), white slate (3), and Marcellus black shale (4) loaded parallel to bedding.

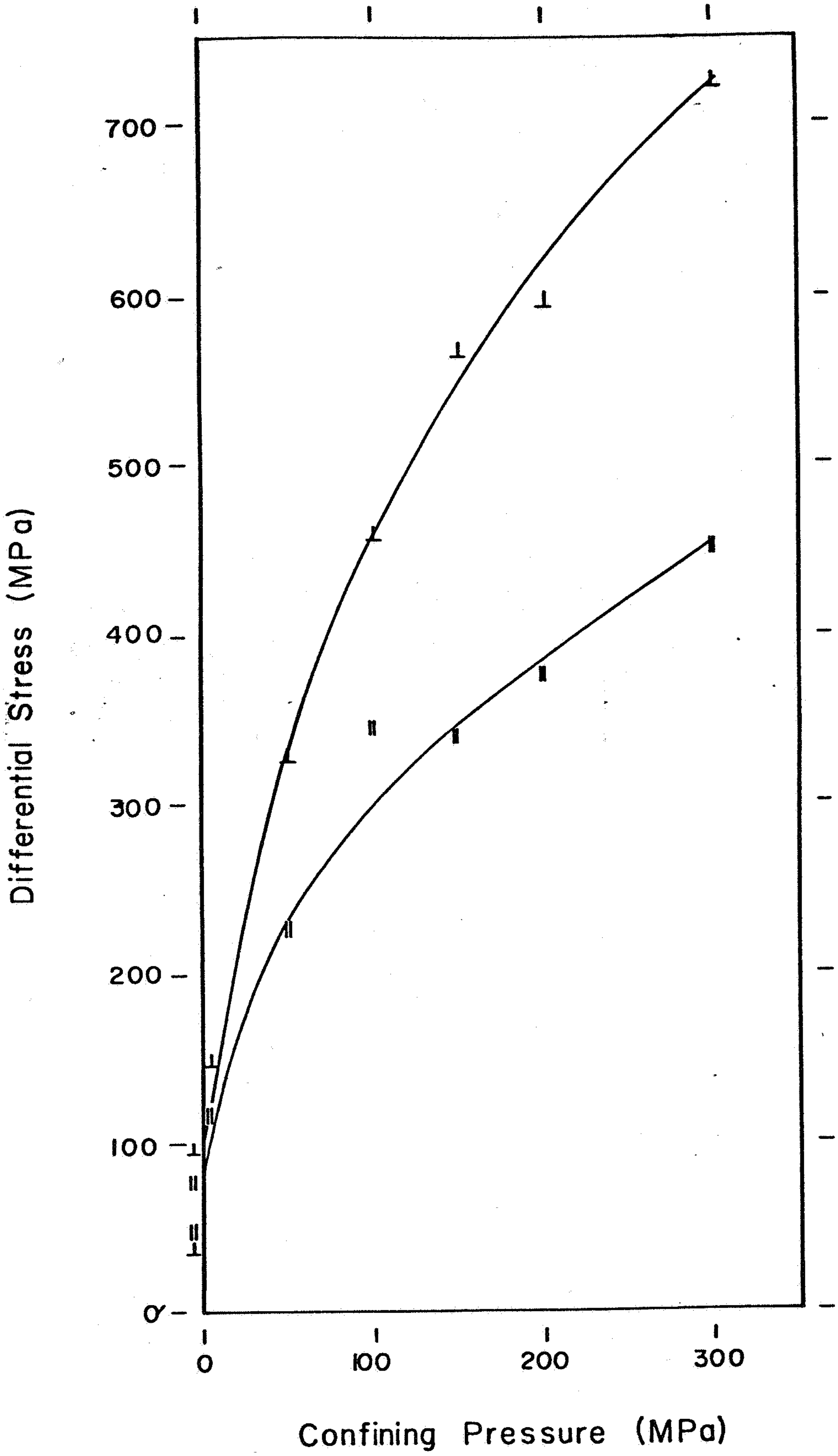

Figure 4. Yield envelopes for the upper grey shale (1) loaded perpendicular (⊥) and parallel (‖) to bedding.

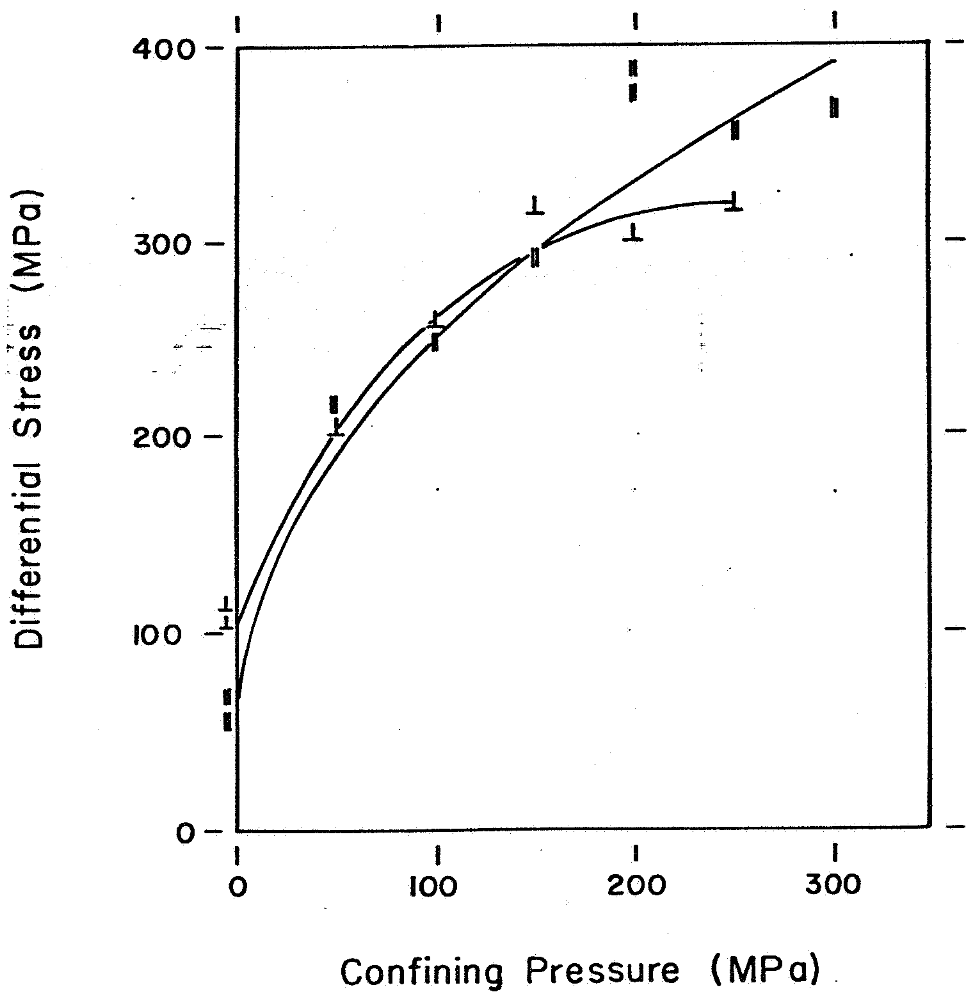

Figure 5. Yield envelopes for the brown gaseous shale (2) loaded perpendicular (⊥) and parallel (∥) to bedding.

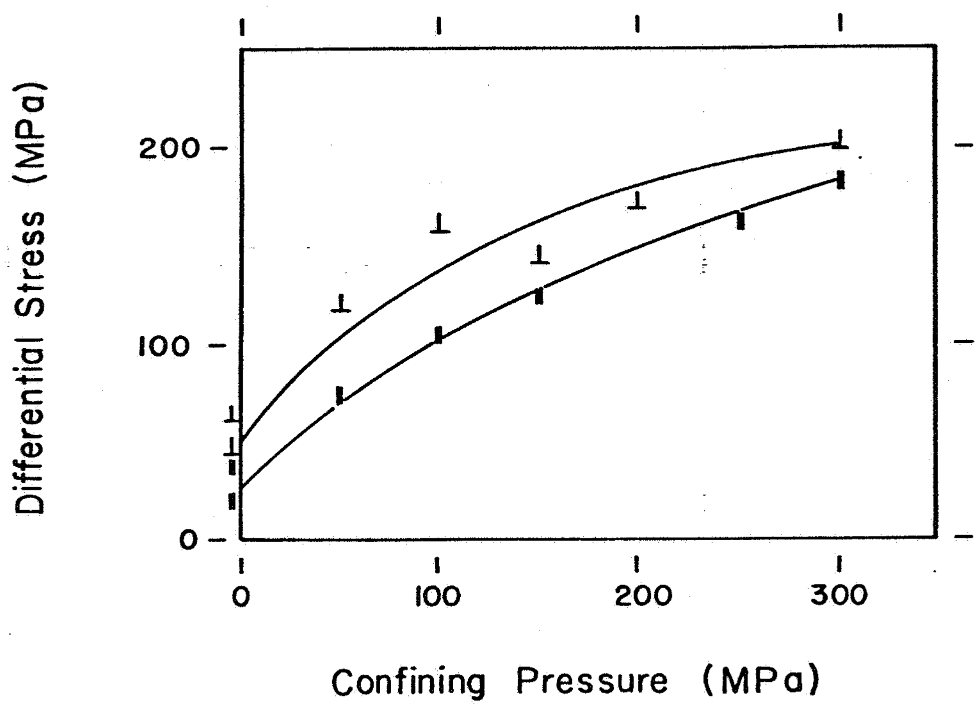

Figure 6. Yield envelopes for the white slate (3) loaded perpendicular (⊥) and parallel (‖) to bedding.

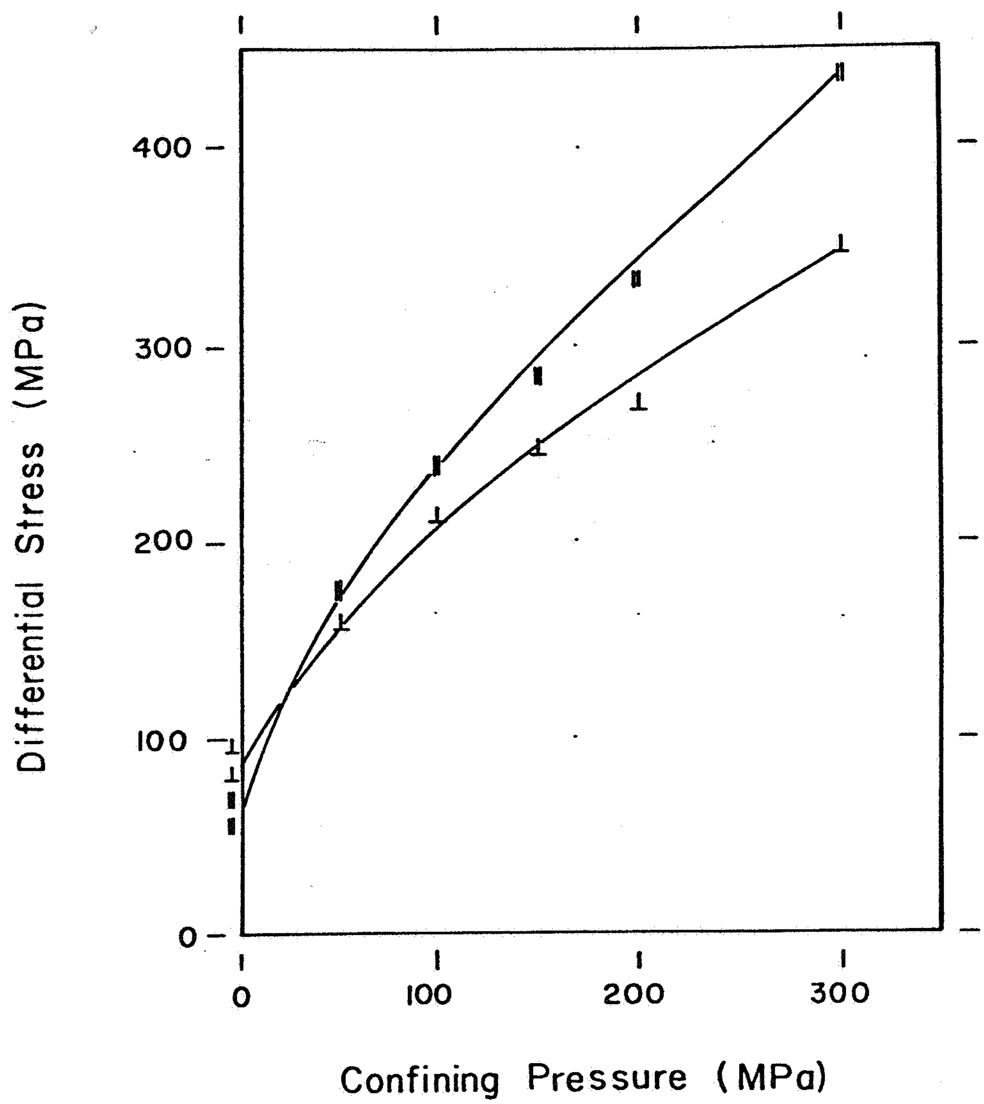

Figure 7. Yield envelopes for the Marcellus black shale loaded perpendicular (⊥) and parallel (∥) to bedding.

in Tables 8 - 15. The following observations can be made with regard to the effects of rock type and bedding planes on strength in compression:

1. The upper grey shale (1) was the strongest and the white slate (3) was the weakest with the brown gaseous (2) and Marcellus black shale (4) being intermediate and approximately equal in strength (Figures 2 and 3).

2. In the unconfined tests there was a definite tendency for the rocks to be stronger when loaded perpendicular to bedding (Figures 4 - 7), but under confining pressure this tendency is reversed for the brown gaseous (2) and Marcellus black shale (4) (Figures 5 and 7).

3. The upper grey shale (1) was brittle under all test conditions and was the most brittle of the four rocks. The other three rocks were more brittle when loaded parallel to bedding (Figure 8).

To establish whether or not any of these tendencies have any regional significance would require more testing.

Compressibility tests up to 4 GPa were run on three of the units from Lincoln County (all except the grey upper shale).[8] Six tests were run on the brown gaseous shale (2) and three tests each on the white slate (3) and the Marcellus black shale (4). Each set of data was fit with a power-law curve by the least squares method for comparison purposes and those curves are plotted in Figure 9 and given below:

Group 2: $P = 90.6\ \epsilon_v^{1.64}$

Group 3: $P = 122.5\ \epsilon_v^{1.58}$

Group 4: $P = 143.0\ \epsilon_v^{1.78}$

where P is pressure (MPa) and ϵ_v is volumetric strain.

The brown gaseous shale is the most compressible of the three with the Marcellus black shale being intermediate and the white slate being the least compressible.

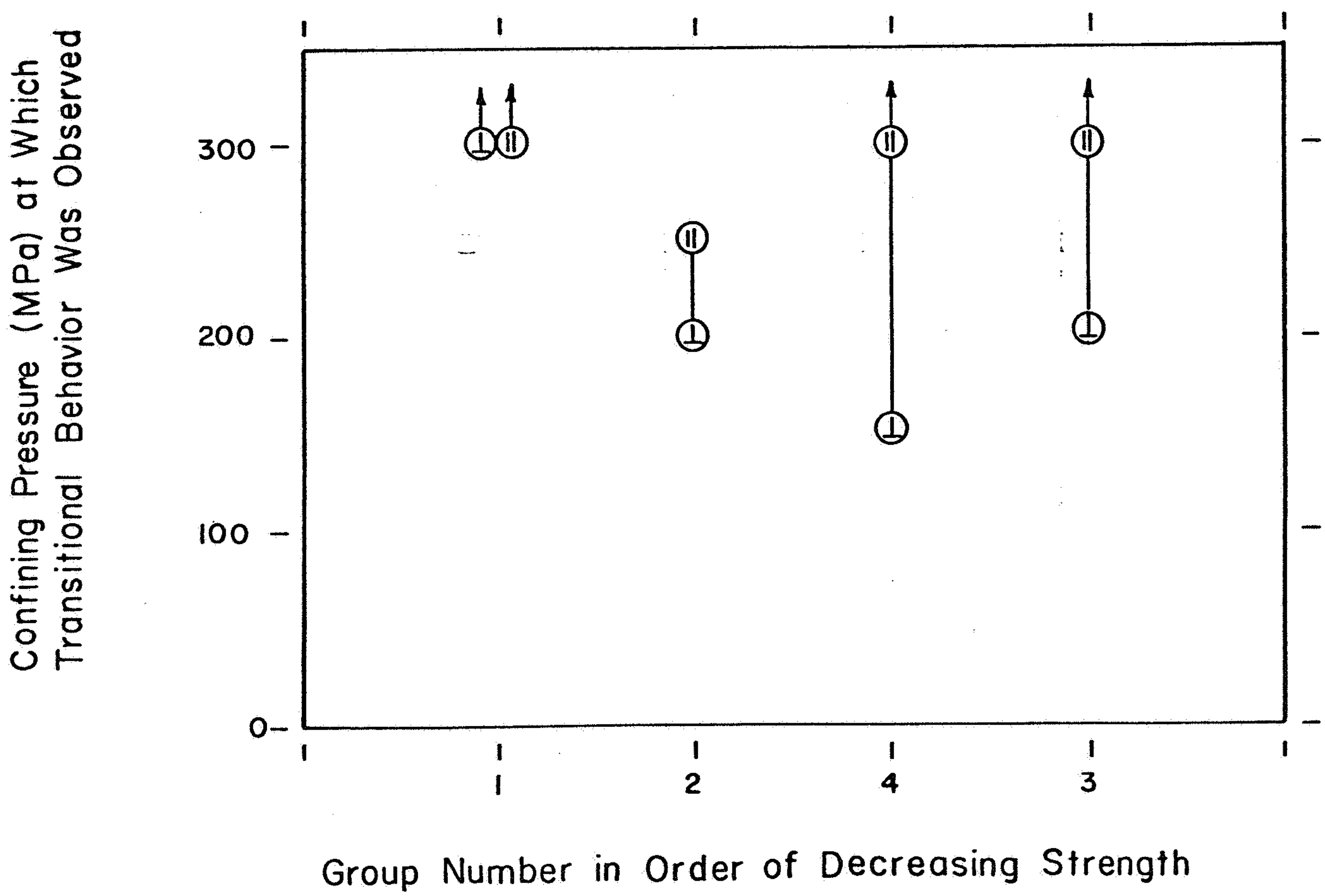

Figure 8. Brittle-ductile transitions for upper grey shale (1), brown gaseous shale (2), white slate (3), and Marcellus black shale (4) loaded perpendicular (⊥) and parallel (∥) to bedding.

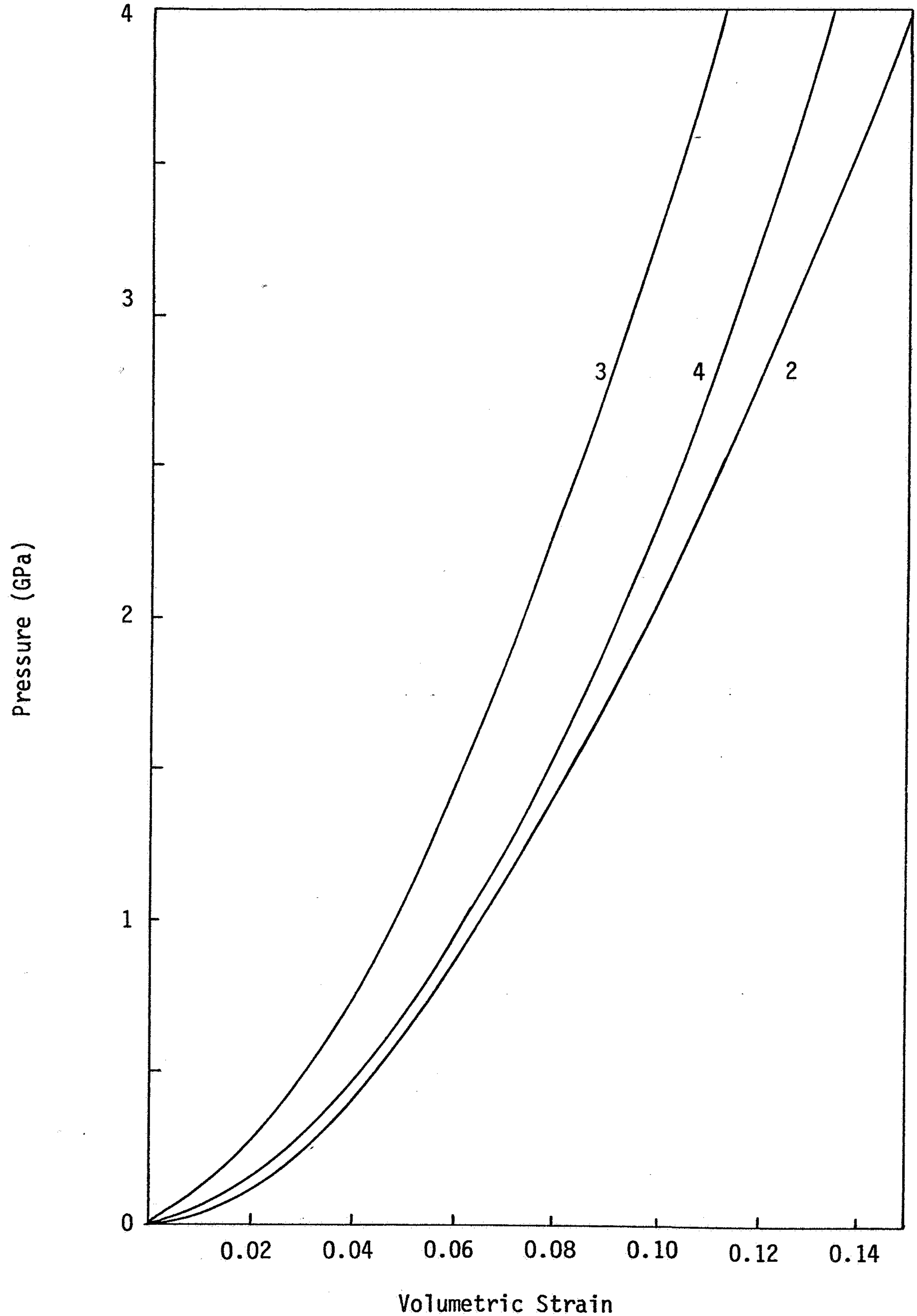

Figure 9. Power-law curves fit to compressibility data on Devonian shales, Groups 2, 3, and 4, from Lincoln County, West Virginia.

For purposes of modeling stimulation treatments in the brown gaseous shale using the STEALTH* code,[15] second-order polynomial curves were fit by the least squares method to yield strengths for the brown gaseous shale loaded parallel to bedding and to compressibility data for the brown gaseous shale. These curves are defined by:

$$Y = 65.84 \text{ MPa} + 2.431 \text{ I} - 0.004746 \frac{1}{\text{MPa}} \text{I}^2$$

where Y is differential stress (MPa), I is mean stress (MPa), and

$$P = -0.01934 \text{ MPa} + 6.740 \text{ MPa } \epsilon_v + 171.0 \text{ MPa } \epsilon_v^2$$

where P is pressure, ϵ_v is volumetric strain. A linear fit to unloading compressibility data for the brown gaseous shale is defined by:

$$P = -1.504 \text{ MPa} + 36.50 \text{ MPa } \epsilon_v$$

Fracture Mechanics: Terra Tek has run four fracture toughness tests on Devonian shale,[11] and the results are presented in Table 16. The values given here are comparable in magnitude to values measured for Indiana Limestone[16] and are about twice values measured for the Nevada Test Site Tuff.[17] Given the general variability of fracture toughness data for rocks and the fact that in two of the four tests failure occurred in an unexpected manner, it is difficult to draw definite conclusions about any preference for a fracture to propagate in a particular shale.

Table 16. Results of fracture toughness tests on Devonian Shale from Lincoln County, West Virginia.

Stratigraphic Unit	Depth (m)	K_{IC} (kPa m)	Remarks
Upper Grey Shale	826	1341	Failure initiated along notch then turned along pre-existing fracture.
	842	1209	Failure ignored notch and occurred on a pre-existing fracture.
Middle Grey Shale	1026	810	Fractured as expected.
Lower Grey	1146	1182	Fractured as expected.

Dynamic Material Properties

Although the static data discussed above provides a good material characterization of the Devonian shales, these data do not define rate effects which may be important during the dynamic yielding and fracturing of the shale by explosive loading. In an effort to define and quantify the dynamic yielding characteristics of Devonian shale, several experiments utilizing a modified split-Hopkinson-bar (SHB) apparatus were performed. These experiments were conceived as logical extensions of modified SHB experiments performed on NTS tuff[17] and on Solenhoffen Limestone and Westerly Granite.[18]

The modified SHB experiments were conducted in collaboration with the Geotechnical Laboratory of Colorado State University. This laboratory has an operational SHB apparatus designed so that electromagnetic, in-material particle-velocity measurements may be made. This apparatus, which is described in detail by Young and Powell,[18] comprises the two traditional suspended bars between which the sample to be tested is placed. An air-driven canon is utilized to accelerate an impact piston against the first (driver) bar. This impact generates a bar stress wave which propagates down the driver bar arriving at the sample. Depending on the sample's impedence and mechanical response, this incident stress wave is partially transmitted through the sample and partially reflected back into the driver bar. By means of strain gages placed upon the two bars, the incident stress wave, the reflected stress wave and the stress wave transmitted through the sample may all be independently measured. Traditionally, an analysis of these waves is made so as to deduce dynamic strength characteristics for the sample material. As samples in SHB experiments typically deform heterogeneously rather than homogeneously, it is valuable to have information on the deformational behavior within the sample proper. Without specific information on heterogeneous sample deformation, sample response can only be inferred as if the sample acted as a homogeneous coupling media between the two bars. By employing electromagnetic velocity gages to measure details of sample deformation, it is possible to calculate directly the stresses and strains acting within various portions of the sample during deformation. The electromagnetic gage techniques which were utilized to measure the details of sample deformation are also described in detail by Young and Powell.[18] Specific gage configurations utilized for axial and radial particle velocity measurements are described by Young et al.[17]

Modified SHB experiments were performed on shale samples oriented so as to measure deformational characteristics for loading both parallel and perpendicular to the bedding. Initially, experiments employing both axial and radial velocity gage configurations were utilized. These gage configurations were identical to those employed in the experiments on NTS tuff.[17] Due to the extremely heterogeneous deformational behavior of the shale samples, however, the radial velocity gage configurations provided data of little value, and only the axial velocity gage configurations were employed for the majority of the tests. All of the tests which were performed on Devonian shale samples are summarized in Table 17.

Table 17. Summary of modified split-Hopkinson-bar tests conducted on Devonian shale.

TEST #	TEST TYPE	BEDDING ORIENTATION TO BARS	IMPACT PROJECTILE VELOCITY (M/S)	INPUT STRESS AMPLITUDE (MPa)	REMARKS
DA-1	Axial	parallel	27.6	542	set up test, no records obtained
DA-2	Axial	parallel	29.1	571	bedding plane parting, poor data
DA-3	Axial	parallel	28.8	565	bedding plane parting, poor data
DA-4	Axial	parallel	11.5	226	good data records
DA-5	Axial	perpendicular	--	---	malfunction of magnetic field, no records obtained
DA-6	Axial	perpendicular	20.2	397	good particle velocity data up to 10 m/s
DA-7	Axial	perpendicular	29.6	581	good particle velocity data up to 7 m/s
DA-8	Axial	perpendicular	28.7	563	bedding plane parting, poor data
DA-9	Axial	perpendicular	19.8	389	good data records
DA-10	Axial	perpendicular	28.9	567	greased sample ends, good particle velocity data
DA-11	Axial	perpendicular	29.8	585	greased sample ends, good particle velocity data
DA-12	Axial	perpendicular	40.2	789	greased sample ends, good particle velocity data
DA-13	Axial	perpendicular	41.6	817	greased sample ends, good particle velocity data
DR-1	Radial	parallel	22.9	450	noisy gage response, poor data
DR-2	Radial	parallel	22.4	440	noisy gage response, #3 gage inverted, poor data
DR-3	Radial	perpendicular	23.3	457	bedding plane parting, poor data
DR-4	Radial	perpendicular	19.7	387	very noisy gage response, poor data
DR-5	Radial	parallel	--	---	late electronic trigger, no record of test
DR-6	Radial	parallel	25.0	491	bedding plane parting, poor data
DR-7	Radial	parallel	20.6	404	bedding plane parting, poor data
DR-8	Radial	parallel	20.9	410	gage configuration modification investigation of bedding parting planes
DR-9	Radial	parallel	10.6	208	gage configuration modification investigation of bedding parting planes

Utilizing the gage configurations for making axial partical-velocity measurements, modified SHB experiments were conducted on Devonian shale samples at nominal impact piston velocities of ten, twenty, thirty, and forty meters-per-second. A brief summary of all the axial velocity tests run on Devonian shale is given in Table 17.

In all of the experiments conducted with loading parallel to bedding (as would be the case in most explosive and propellant stimulation treatments) sample deformation was characterized by severe splitting of the sample along bedding planes. Due to the dominant control of sample failure by the bedding plane structure, sample deformation was quite heterogeneous and, as has been noted for data from the radial particle velocity gages, data from these tests was of limited value. Data from tests with the samples oriented with their bedding perpendicular to the bars were of generally good quality. As frictional end effects did appear to influence adversely sample failure (making it more heterogeneous) several tests were performed with a light grease coating applied to the ends of the samples. Data from these tests, DA-10 to 13, were the most consistent and the most suitable for analysis.

With the axial velocity data obtained from three different positions within the SHB sample, it is possible to calculate the average stress-strain relationships existing in the sample during its dynamic deformation. Calculation of the dynamic stress-strain relationships involves integrating the velocity curves at any of the gage positions with an appropriate description of the phase velocity for wave propagation along the sample. As discussed by Fowles and Williams[19] two characteristic phase velocities are defined for one dimensional wave propagation. These two phase velocities are defined as:

$$c_p = \left(\frac{\partial h}{\partial t}\right)_p,$$

$$c_u = \left(\frac{\partial h}{\partial t}\right)_u,$$

where h is the Lagrangian coordinate position, t is time and p and u indicate the value of the derivative at constant p-wave stress and particle velocity respectively.

These phase velocities represent the speed at which stress or particle velocity information is propagated along the sample. For a steady wave c_p and c_u would be equal and would equal the classical compressive wave velocity for the material. When equal particle velocities were measured at three gage positions, a parabolic fit was utilized to determine the phase velocity relationships along the sample. When only two gages measured a given particle velocity a linear relationship was utilized. The axial stresses acting within the sample during deformation were obtained by numerically integrating the equation:

$$d\sigma = \rho_o c_p \frac{\partial u}{\partial t} dt,$$

which describes the relationship between stress, phase velocity, particle velocity and density. A similar numerical integration of the equation:

$$d\epsilon = \frac{1}{c_u}\frac{\partial u}{\partial t} dt,$$

describing the relation between strain and particle and phase velocity, yields a description of axial strain vs. time at the various gage positions. By combining the stress vs. time and strain vs. time data, a dynamic stress-strain curve is obtained. The stress-strain curves calculated for tests DA-9 thru DA-13 all show dynamic Young's moduli (12.57 to 20.0 GPa) somewhat lower than previously determined static moduli.[11] In none of these tests was significant yielding observed in the calculated stress-strain curves. The peak axial stress of 80 MPa (.8 kbar) measured in test DA-9 does provide a rough measure of a minimum "dynamic" strength for the shale. That other tests with much higher piston impact velocities (eg. DA-13 at 41.7 m/s) did not provide higher in-material particle velocities indicates that sample failure was occurring at around 70-80 MPa. This inferred strength is quite comparable to the static unconfined compressive strength obtained on a brown gaseous shale (ρ=2.51).[8] As the lower density (ρ=2.39) of the SHB samples implies a higher organic content for the rock, the unconfined compressive strength for the SHB test shale would be expected to be lower than both the dynamic strength and the static strength for the brown gaseous shale. As neither static data nor high quality dynamic data are available on the SHB test shale, it is not possible to quantify the true high strain-rate increase in rock strength. Based upon the data available, however, it appears that true dynamic strengths are only slightly higher than static strengths, as is the case for all other rocks studied.[17,18]

Conclusions

The several labs working on various aspects of Devonian shale material properties have generated a considerable volume of data, but unfortunately most of it is so site-specific that it is difficult to draw any regional or generic conclusions about most of the properties. One exception to this is the density measurements, which have been taken from enough localities so as to form a basis for regional analysis and which have been taken in such a way as to allow correlation with lithology. In general the black and brown organic-rich shales have lower densities than the grey shales because the organic phase has a lower density than the inorganic phase. This is an important correlation because it establishes a relation between something measurable from logs and the thing that is ultimately being sought, hydrocarbons.

Of course, producing more gas depends also on finding and tapping reservoirs in which the hydrocarbons collect, and this is where mechanical properties begin to play an important role. One would like to build on the relation between lithology and density by establishing similar relations between lithology and the various mechanical properties, but the data have not been generated in such a way as to allow this type of analysis. A prime example of this is the elastic constant data generated by Terra Tek. In an attempt to simulate in situ conditions, core of different lithology was tested at different confining pressures, according to the depth from which the core was taken. This makes the data useful for the particular site in question, but makes it impossible to draw any conclusions about the variation of elastic constants with lithology or with confining pressure, since the two effects cannot be separated.

If suitable elastic constant data did exist for drawing the desired correlations, the next step would be to draw similar correlations for the other static and dynamic mechanical properties. The data generated by LLL on static strength and ductility comes very close to allowing such a correlation with Terra Tek's elastic constant data. The tests were run on core from the same well (Columbia Gas Well #20403, Lincoln County, West Virginia), and roughly the same stratigraphic division was made by each lab. But examining the data in detail does not lead to the kind of conclusions one would like to make. For example, the yield curves for the brown and black shales fall almost on top of each other, but one of the grey shale curves (upper grey shale of Group 1) is much higher than the organic shale curves, and the other (white slate of Group 3) is much lower. One wonders whether these relationships hold in general or whether they are peculiar to this particular site. One thing that makes one suspect that the behavior of Group 3 may not be representative is the fact the term "white slate" was used for what is a predominantly grey shale unit. The choice of the term "slate" suggests that the rock was fissile, which may account for its relative weakness. Terra Tek pointed out that local stratigraphic variations adversely affected their data in the case of their lower brown (Marcellus) shale where they obtained abnormally high Young's moduli and densities. A more systematic approach to the selection of core, both regionally and stratigraphically would render a much more useful data base.

For the purposes of modeling and stimulation design, passable material property data exist for the Devonian shale in Lincoln County, West Virginia, and sufficient density data exist for regional and lithologic trends to be established. Static mechanical property data, on the other hand, have not been generated in such a way as to allow generic and regional trends to be identified. Such trends could play an important role in selection of one of the several stimulation techniques being considered for a given site.

The data base on dynamic shale properties is much more limited. The dynamic moduli and tensile strength values obtained by Carter and Olinger[20] and Olinger[21] represented the only significant data available. The elastic moduli are based upon ultrasonic velocities while the tensile strengths were determined from very high-rate (plate-slap) tests. Efforts to obtain data at the loading rates and stress amplitudes representative of explosive and tailored-pulse-loading treatments were frustrated by the extremely anisotropic and heterogeneous failures of the samples. The limited data do indicate that large-strain dynamic moduli and dynamic yield strength are not vastly different from statically determined values. Thus, the use of static data would be a suitable first approximation for input to numerical calculations of explosive and tailored-pulse-loading treatments.

Additional experimental techniques and the consequent data will be required to properly describe the dynamic material properties of Devonian shale. Such an improved description of shale properties will be required for site specific calculations and for fine tuning the loading characteristics of explosive or tailored-pulse-loading treatments to specific shale wells. The existing data base is adequate for parameter sensitivity-type calculations and for predicting the general effects of explosive / propellant treatments.

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