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INDIRECT AND DIRECT TENSILE BEHAVIOR OF DEVONIAN OIL SHALES

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INDIRECT AND DIRECT TENSILE BEHAVIOR OF DEVONIAN OIL SHALES[a]

by

K. P. Chong[1], J. L. Chen[2], G. F. Dana[3] and J. A. Weber[4]

ABSTRACT

Ultimate indirect tensile strengths of Devonian oil shales across the bedding planes is a mechanical property parameter important to predicting how oil shale will break. This is particularly important to *in-situ* fragmentation. The Split Cylinder Test was used to determine the indirect tensile strengths between the bedding planes. Test specimens, cored perpendicular to the bedding planes, representing oil shales of different oil yields taken from Silver Point Quad in DeKalb County, Tennessee and Friendship in Scioto County, Ohio, were subjected to the Split Cylinder Test. Linear regression equations relating ultimate tensile strength across the bedding planes to volume percent of organic matter in the rock were developed from the test data.

In addition, direct tensile strengths were obtained between the bedding planes for the Tennessee oil shales. This property is important for the design of horizontal fractures in oil shales. Typical results were presented.

INTRODUCTION

In-situ retorting requires fracturing the oil shale to create sufficient permeability. Fracturing shales in place entails breaking the bedding planes. Since oil shale and most rocks are weaker in tension than in compression, practically all fractures across the bedding planes are caused by tension. Hence, ultimate indirect tensile strengths across the bedding planes are important in vertical fracture studies (1, 2). On the

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other hand, direct tensile strengths between the bedding planes are important in horizontal fracture studies (3).

Most of the mechanical characterization investigation of oil shale appearing in the literature (1, 2, 3, 4, 5, 6, 7, 8) is on the Green River Formation located in the tri-state area of Colorado, Utah and Wyoming. The ultimate tensile strengths of the oil shale of the Green River Formation in the tri-state area have been reported (1, 2); however, tensile strengths of the Devonian oil shales in the eastern states are still lacking.

Split Cylinder Testing, which measures average (indirect) tensile strength across many bedding planes, yields more representative information than direct tension testing (1, 2, 9). Consequently, Split Cylinder Testing was used to obtain indirect ultimate tensile strengths across bedding planes. Test cylinders were cut perpendicular to bedding planes at many different depths in order to obtain comprehensive representation and a broad range of organic contents.

Direct tensile strengths were obtained by pulling between the bedding planes (3). Hence these strengths indicate the bonding strength between bedding planes.

Oil shales of Devonian and Mississippian Ages are found in 11 eastern states (10, 11). They range in thickness from a continuous 4.6 m (15 feet) of black shale in Tennessee to an interbedded sequence of black and gray shale of slightly more than 915 m (3000 feet) in western New York (12). The eastern shales were deposited in marine environments which reflected low clastic influx, high organic activity, and a stratified water column. In contrast, the western oil shales were created in lacustrine (lake) environments of Lake Gosuite and Lake Uinta some 40 to 50 million years ago. About 25 different stratigraphic names are found in the literature defining rocks of essentially the same age (13). The major terms are Antrim (Michigan), Ohio Shale (Ohio), New Albany (Kentucky), and Chattanooga (Tennessee and Alabama). Fischer assay of the best parts of the deposits averages 46 to 54 ℓ/t (11 to 13 gal/ton), but a process called Hytorting yields about twice as much oil from these strata by providing additional hydrogen to the organic matter as it decomposes. Presently, the process is expensive, but improvements could lead to its commercial application.

Differences in mineral content exist between eastern and western shales. Eastern shales generally contain large amounts of illite and mixed layer clays, while the matrix of western shales shows variable clays and dolomites. Eastern shales contain uranium, an element found in very small quantities in western shales.

The total resource for black Devonian oil shales of the United States (10) has been estimated as high as 0.45×10^{12} kℓ (2.8×10^{12} barrels), as compared to 288×10^9 kℓ, or 1800×10^9 barrels (14) of oil in place of all grades in western deposits.

Development of eastern oil shales may be slower and on a smaller scale than western shales because of thickness, richness, and associated mineral content. Other factors, such as proximity to the market, the price of petroleum products, regional demand, etc., affect such development.

THEORY

Critical review and analysis of the Split Cylinder Test have been presented (1, 15). The Split Cylinder Test, or the "Brazilian" Test, is an established method used primarily to determine the tensile strength of concrete (16) and other brittle materials having much higher compressive strengths than tensile strengths (9, 15). Basically a circular cylinder or disk is compressed with concentrated line loads, P, across a diameter (Fig. 1). Ideally the tensile failure will occur along the loaded diameter, splitting the cylinder into two halves.

Referring to Fig. 2, for any point C within the disk, the classical theory (2, 17) yields:

$$\sigma_x = -\frac{2P}{\pi bd}\{d(\frac{\sin^2\theta_1\cos^2\theta_1}{y_1} + \frac{\sin^2\theta_2\cos^2\theta_2}{y_2})-1\} \quad . . . . . (1)$$

$$\sigma_y = -\frac{2P}{\pi bd}\{d(\frac{\cos^4\theta_1}{y_1} + \frac{\cos^4\theta_2}{y_2})-1\} \quad . . . . (2)$$

$$\tau_{xy} = \frac{2P}{\pi bd}\{d(\frac{\sin\theta_1\cos^3\theta_1}{y_1} - \frac{\sin\theta_2\cos^3\theta_2}{y_2})\} \quad . . . . (3)$$

where,

σ_x, σ_y = normal stress in x, y directions respectively;

τ_{xy} = shear stress;

b = thickness of disk;

d = diameter of disk; and

P = total line load.

Since the classical theory is valid for most areas of the cylinder, except in the proximity of the loads (1), it is used to compute the average ultimate tensile strength of the rock. Using the classical theory, along the loading plane both θ_1, and θ_2, are zero. Under ultimate load Equation 1 reduces to:

$$\sigma_u = \frac{2P_u}{\pi d} \quad . . . . (4)$$

where σ_u = ultimate tensile strength (stress) in the x-direction, and P_u = ultimate (maximum) load per unit thickness of the cylinder. Subsequently,

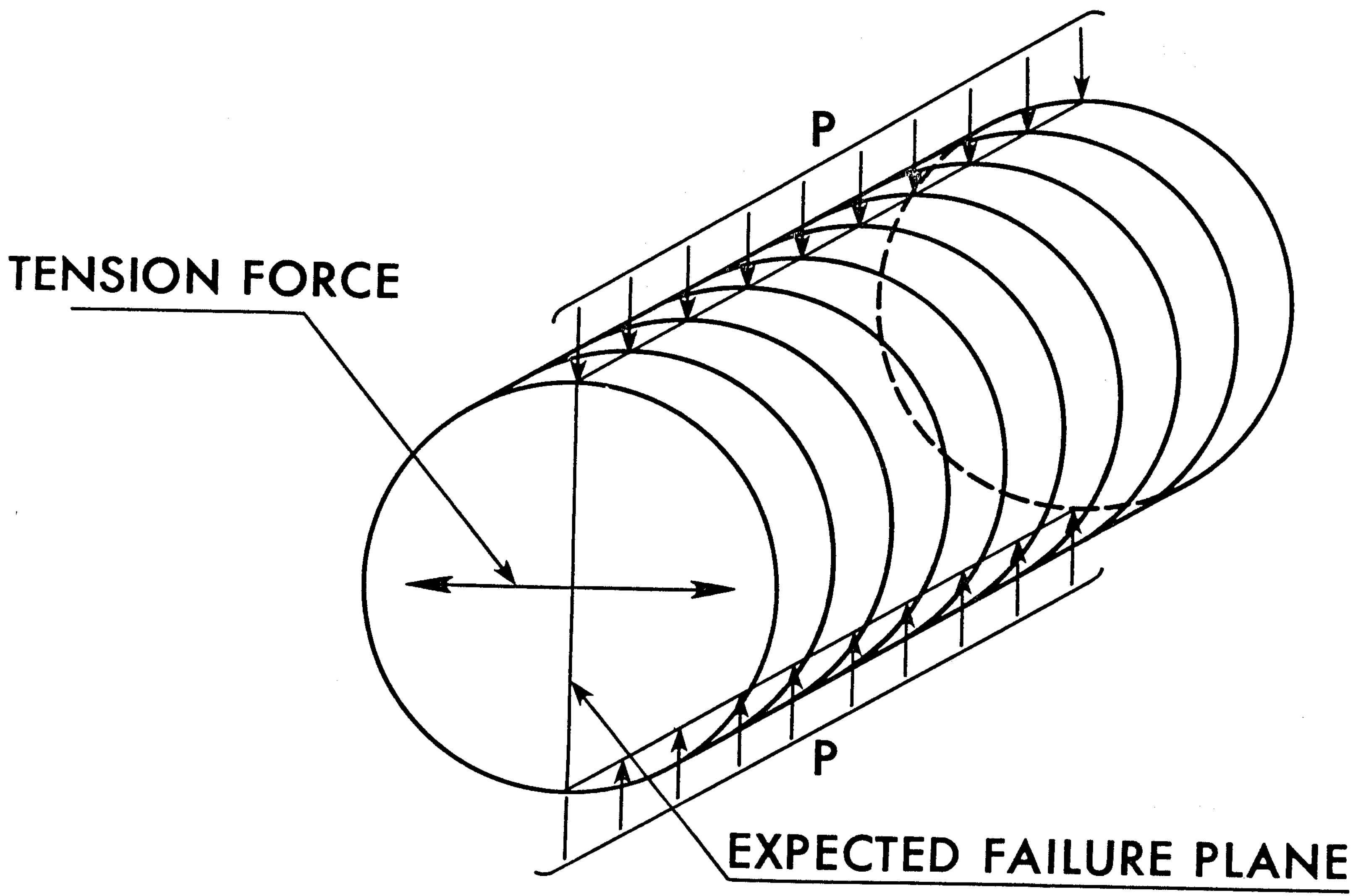


Fig. 1 Loading with bedding planes vertical

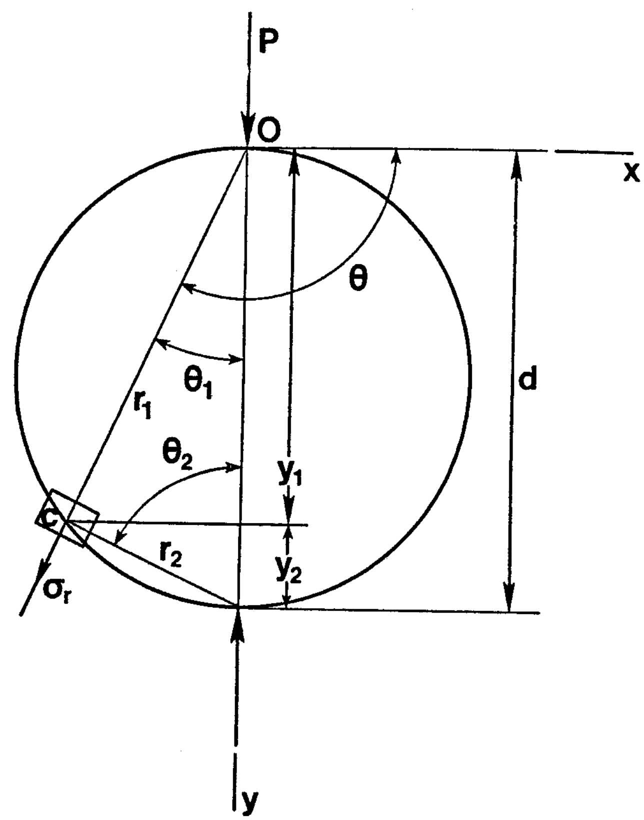


Fig. 2. Forces acting on a circular cylinder

Equation 4 is used in this paper. Wang and Chong (18) showed that the above formula also holds for transversely isotropic materials if plane elasticity is assumed.

For direct tensile testing, the tensile stress between bedding planes, σ_{ud}, is given by,

$$\sigma_{ud} = \frac{4Q}{\pi D^2} \quad \ldots \quad (5)$$

where,

Q = axial ultimate load applied along the axis of the cylindrical specimen cored perpendicular to bedding planes (Fig. 3).

D = diameter of cylinder.

EXPERIMENTAL

Sample Preparation

Oil shale occurs in beds which are composed of numerous very fine varves; and while these vary considerably in oil content vertically, they are remarkably consistent in a horizontal direction. The same bed, or group of beds, can be identified over many, many kilometers. Sampling is keyed on the transverse isotropy of oil shale (5). The samples tested in this experiment were taken from the Gassaway and Dowelltown Members of DeKalb County, Tennessee (19); and Cleveland Huron Members at Friendship in Scioto County, Ohio (20).

Field cores measuring 15.2 cm (6 inches) and 10.2 cm (4 inches) in diameter were drilled respectively from the geologically similar Tennessee and Ohio oil-shale deposits (19, 20). Using a diamond-tipped, water-cooled core drill, test cores were drilled from the field cores perpendicular to bedding planes. Nominal diameters of the test cores for Split Cylinder Tests were 4.5 cm (1-3/4 inches) for Tennessee shales and 3.2 cm (1-1/4 inches) for Ohio shales. Lengths ranged from 3.8 cm (1-1/2 inches) to 1.3 cm (1/2 inch) for the smaller specimens. These specimens provided a range of oil yields representing Devonian oil shales. Since oil shale is a vertically inhomogeneous rock, care was taken to select as uniform a sample as possible. Layers with obviously varying composition, with major elastic inclusions, or with existing faults were avoided (2, 5). The over-cores were saved to maintain a record of each sample's stratigraphy and structure.

In addition direct tension testing was done on selected cylindrical specimens about 4.5 cm (1-3/4 inches) in diameter and 15.2 cm (6 inches) long. The ends of all cylindrical specimens were square-sawed and ground.

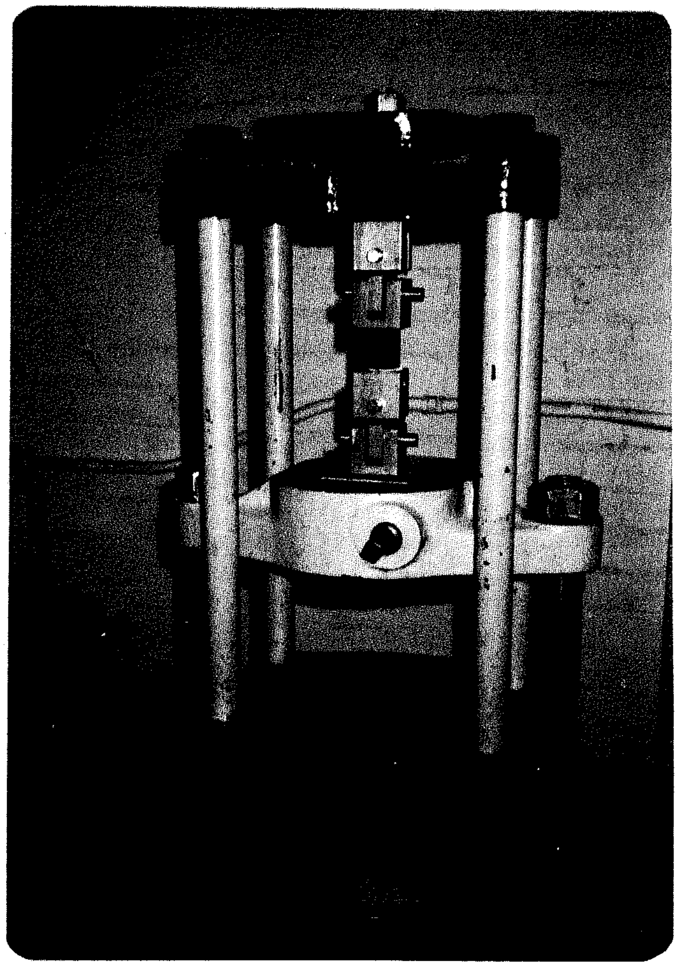


Fig. 3. Apparatus for direct tensile testing

Procedure

A Tinius Olsen Universal Testing Machine with ranges up to 267 KN (60,000 pounds) was used for loading. The loading head consisted of a steel plate connected to a ball bearing so that the load was applied uniformly along the side of a sample. For Split Cylinder Testing load was applied to the cylindrical specimens diametrically along the side (Fig. 1). To insure the load was applied diametrically, the specimen was inserted into a simple fixture (Fig. 4) and marked. Two narrow bearing strips of plywood were placed between the specimen and the upper and lower bearing blocks of the testing machine. Load was applied with a strain rate of approximately 0.5% per minute until tensile cracks appeared and failure was complete. Test data with the failure planes deviated from the loading planes were neglected. The coincidence of failure and loading planes indicated competent rocks whose strength governs in modifying the rocks in place (1, 2, 21).

The direct tension testing is modeled after the method devised by Young, et al. (22). The oil shale specimen was adhered to the gripping blocks (Fig 5) which had two degrees of freedom to eliminate any bending to the specimen. After curing, the gripping blocks and specimen were carefully assembled in the testing machine (Fig. 3) and pulled. The adhesives used were Epoxi-Patch 608 Clear Quick Set, which cured in about 1 hour at room temperature with a bonding strength of about 6.9 MPa (1 ksi) and 907 Pale Green High Performance which cured in about 2 hours at 60°C with bonding strengths in excess of 6.9 MPa (1 ksi). Since the interbedding strengths of Tennessee shales are quite weak, it turned out that the 608 Clear Quick Set was adequate. During testing, the weakest layer broke first. The load was recorded and the stratigraphic location of the break was noted (22). The broken specimen was repaired and stuck together with the adhesive, cured, and pulled again, failing the next weakest layer. The process was repeated until there were horizontal fractures approximately every 3 cm (1.18 in.).

RESULTS AND ANALYSIS

Three oil-shale parameters which may be associated with variations in mechanical properties of oil shale are organic matter content, mineralogy, and anisotropy perpendicular to the bedding planes (23). The testing method described here eliminates anisotropy as a significant parameter because the principal planes coincide with the bedding planes (18). Statistically, effects of mineralogic variations are insignificant among geologically similar samples (2). Consequently relationships of test results with organic matter volume in the tested samples were examined.

Organic matter content of the specimens was estimated from oil-yield results from the modified Fischer retort assay procedure (24). Smith (23) pointed out that the volume fraction of organic matter in the rock was the primary factor affecting mechanical properties, indicating that linear relationships of mechanical properties with organic matter volume would exist while weight measurements of organic content should show strongly non-linear results. The organic content in percentages by volume (O_c) has been calculated from the oil yield in gallons per ton (M) using the relationship developed by Smith (23), with 1.07 as the average density of Green

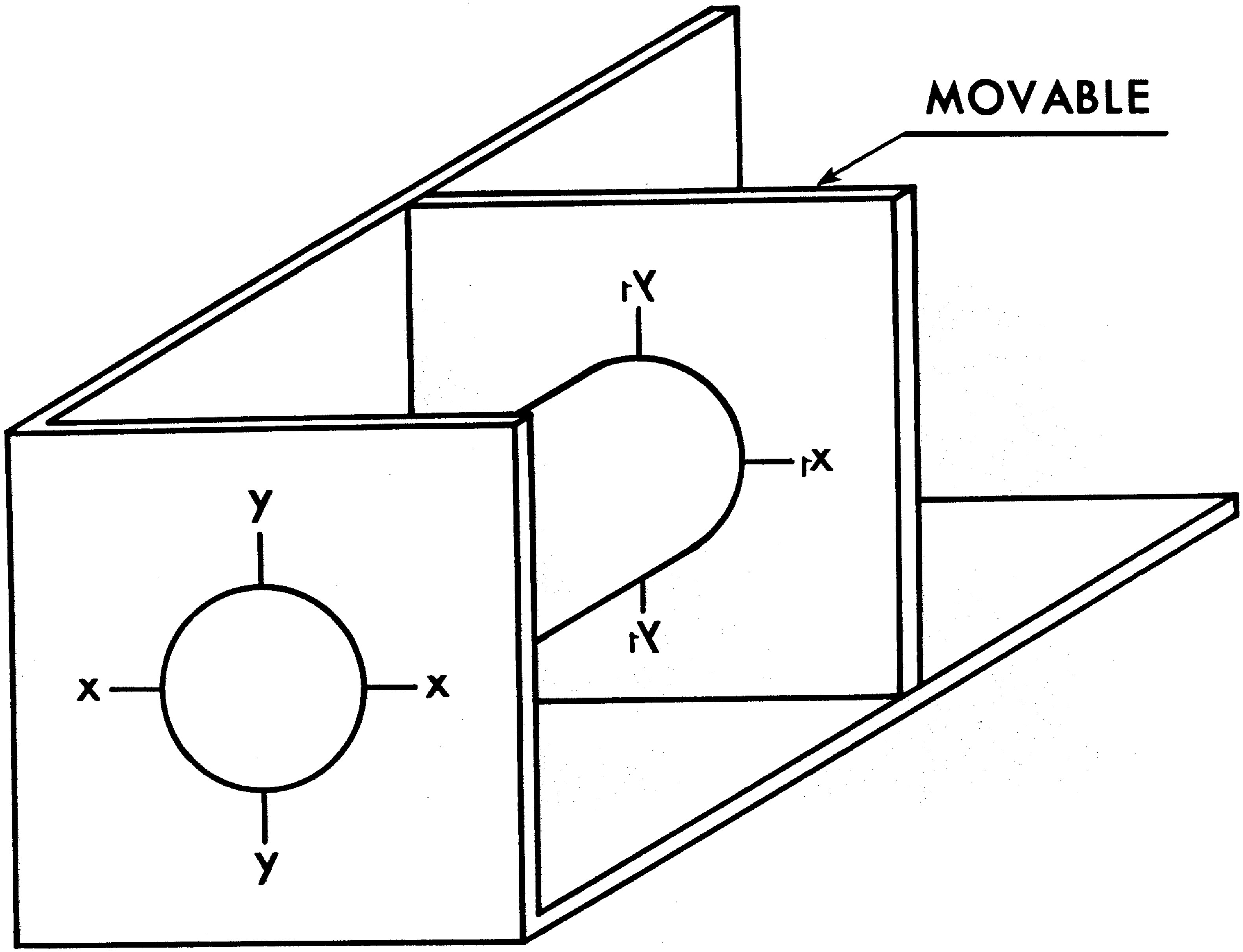


Fig. 4. Apparatus for marking coordinate system

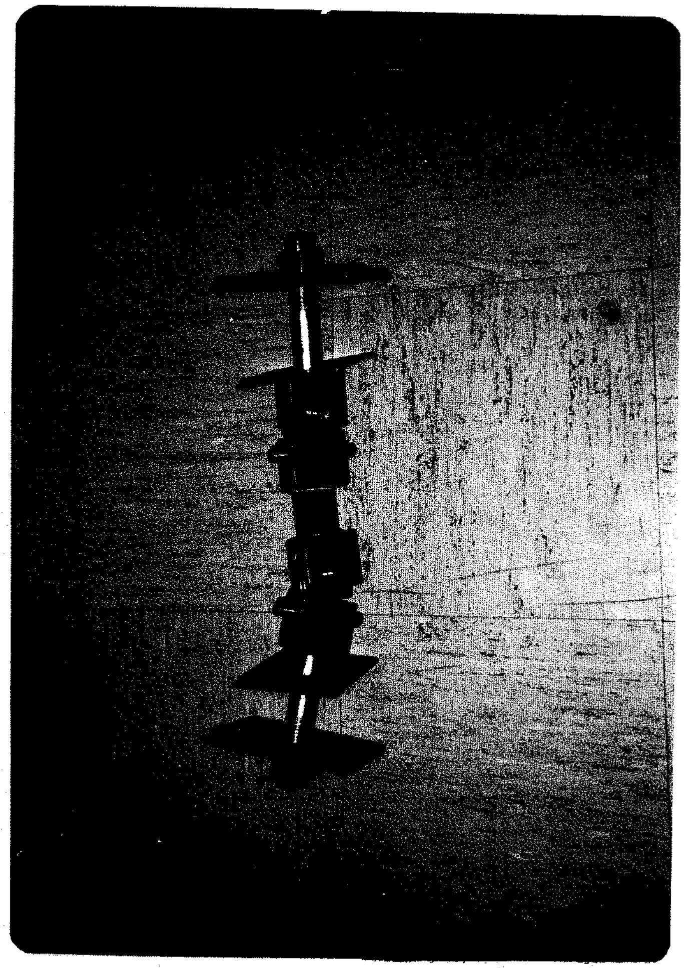


Fig. 5. Gripping blocks for direct tensile testing

River Formation organic matter (23). Unfortunately such relationships are still non-existent for Devonian oil shales. Based on computer testing on limited data, the following relationship is an estimate of the organic volume, investigated by Smith and Chong (25),

$$O_c = \frac{188.36\ M}{M + 73.63} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Applying regression analysis on the data, the following linear relationships between ultimate tensile stress (σ_u) in MPa and the organic matter volume percentage in the Devonian oil shale were obtained:

(a) For Tennessee oil shale:

$$\sigma_u = 15.279 - 0.07836\ O_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Coefficient of determination: $r^2 = 0.6065$

No. of data: $N = 15$

Mean values: $\overline{\sigma}_u = 13.24$ MPa

$\overline{O}_c = 25.91\%$

Standard error of estimate: $s = 0.33$ MPa

(b) For Ohio oil shale:

$$\sigma_u = 10.996 - 0.1818\ O_c \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

$r^2 = 0.6359$

$N = 19$

$\overline{\sigma}_u = 6.46$ MPa

$\overline{O}_c = 24.94\%$

$s = 0.63$ MPa

Equations 7 and 8 are plotted in Figs. 6 and 7 together with the test data points. Results of direct tension testing are shown in Figs. 8 to 10. Existing fractures were indicated by dotted lines. Most horizontal fractures occurred at stresses below 2.8 MPa (400 psi).

CONCLUSIONS

The indirect tensile strengths of the Devonian oil shales are slightly weaker than those of the Green River Formation (1), especially for the Ohio oil shale. The Tennessee oil shale is similar in strength and behavior to the Utah or Colorado oil shales (1). The indirect tensile strength of the Ohio oil shale (as indicated by Eq. 8) is much lower. This may be due to the high clay contents which tended to crack even though every attempt was made to preserve the moisture in the specimen.

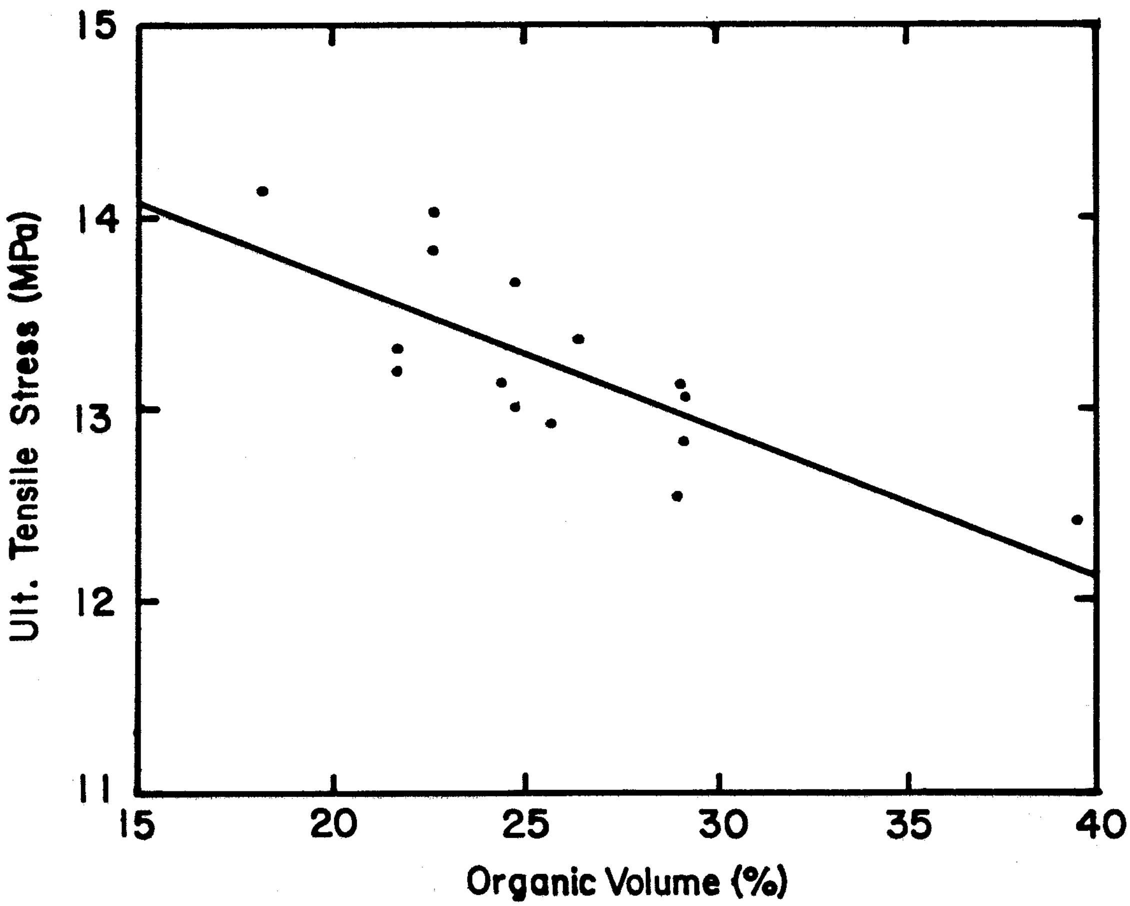
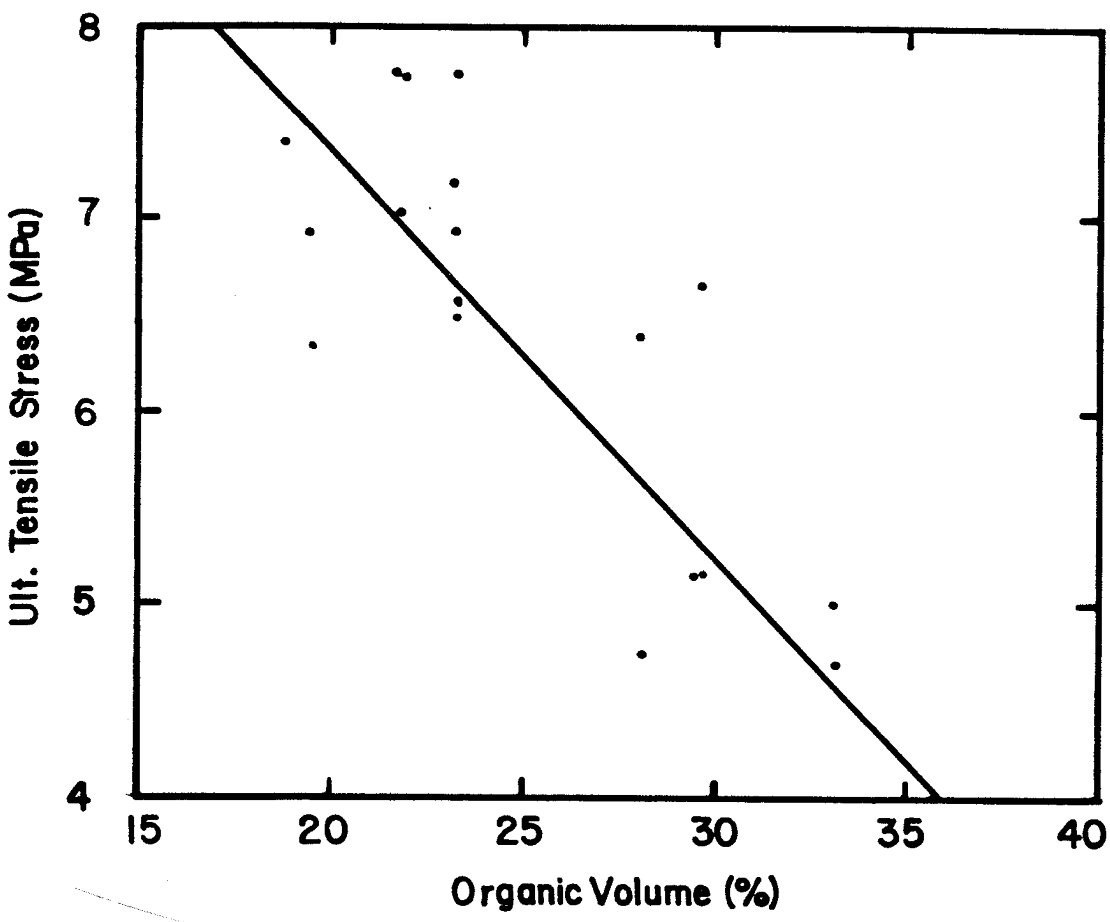


Fig. 6. Indirect tensile stress of Tennessee oil shale

Fig. 7. Indirect tensile stress of Ohio oil shale



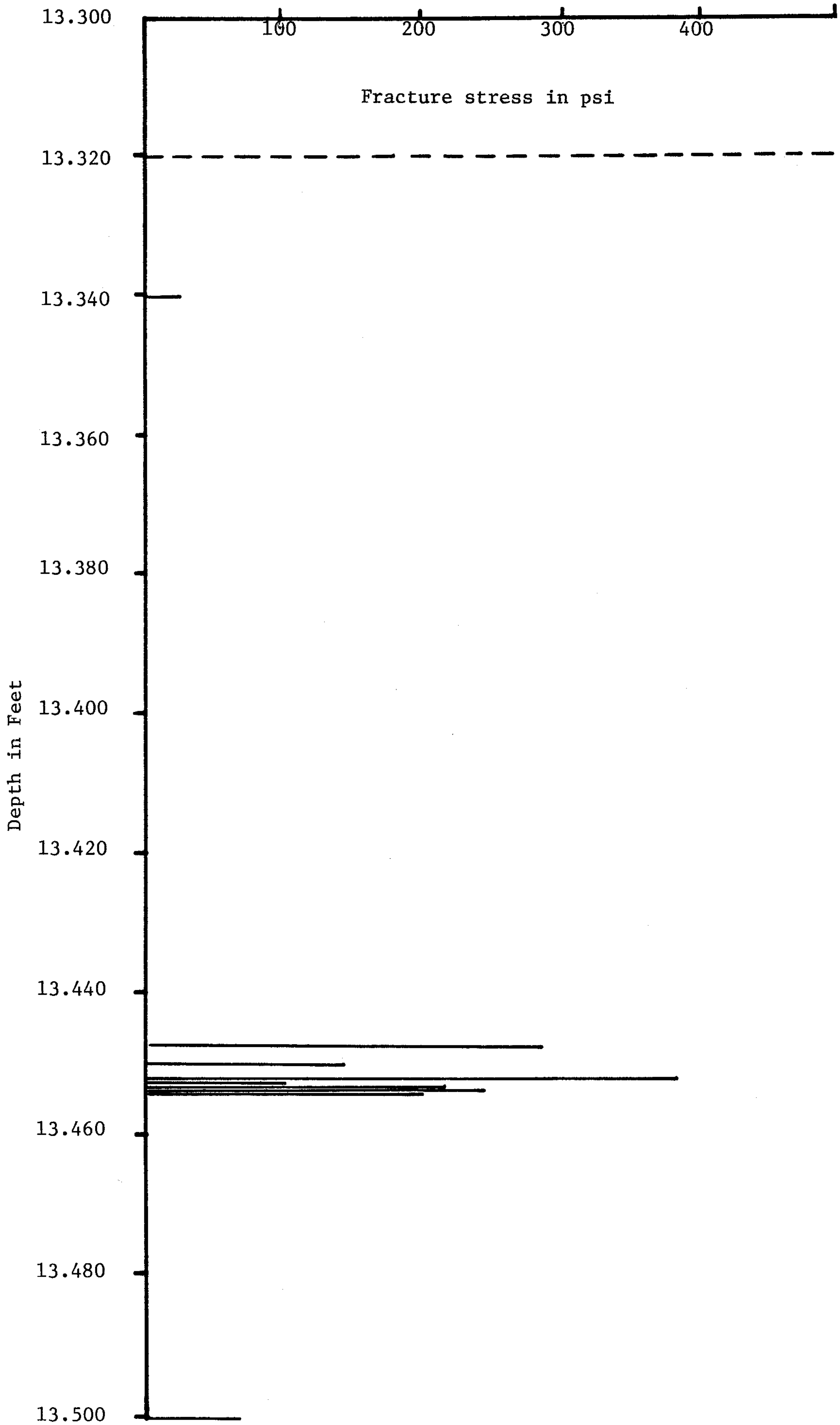


Fig. 8. Direct tensile testing of Tennessee oil shale around 13 feet depth. (Note: 1 ft = 0.305 m, 1 psi = 6.9 kN/m^2)

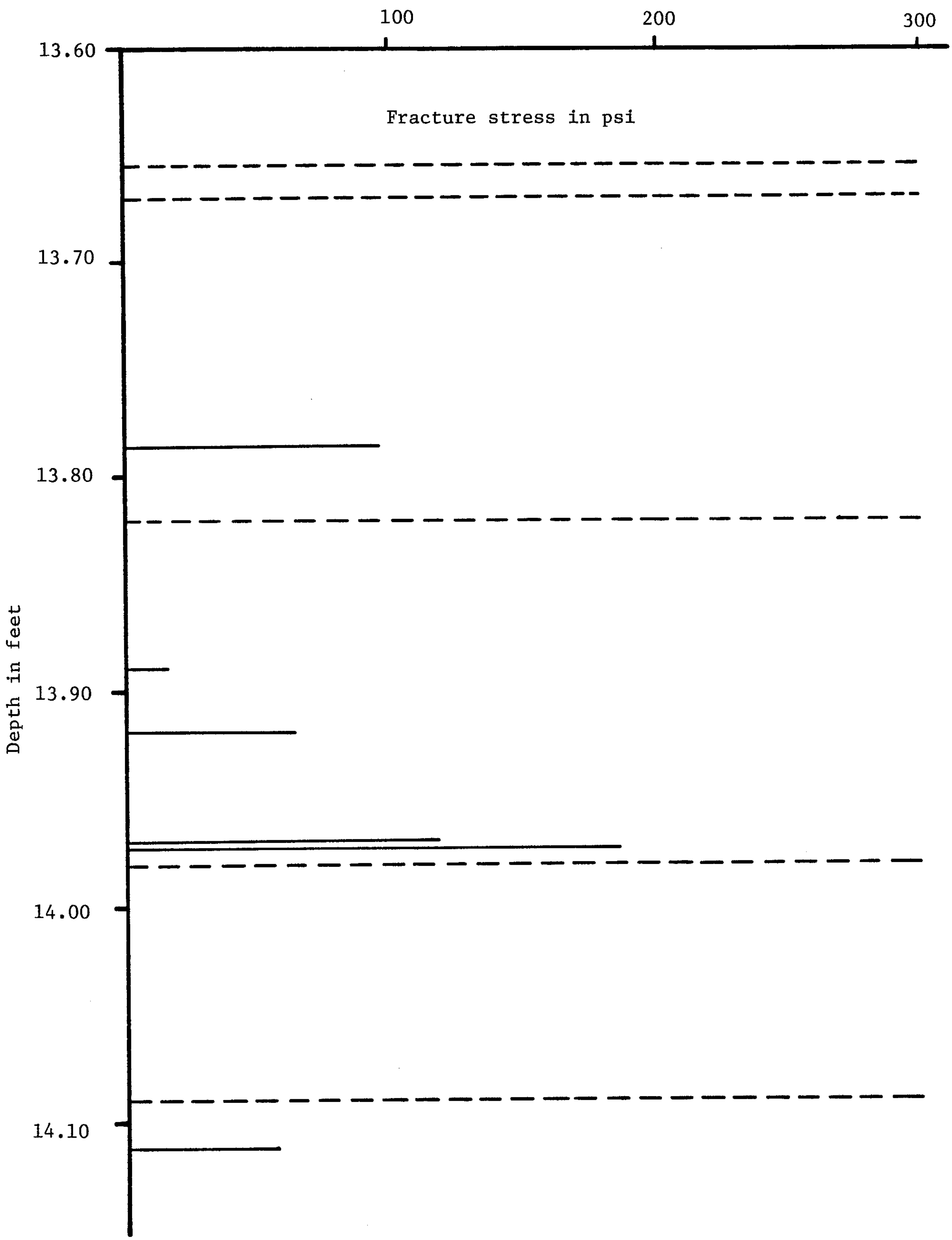


Fig. 9. Direct tensile testing of Tennessee oil shale around 14 feet depth. (Note: 1 ft = 0.305 m, 1 psi = 6.9 kN/m^2)

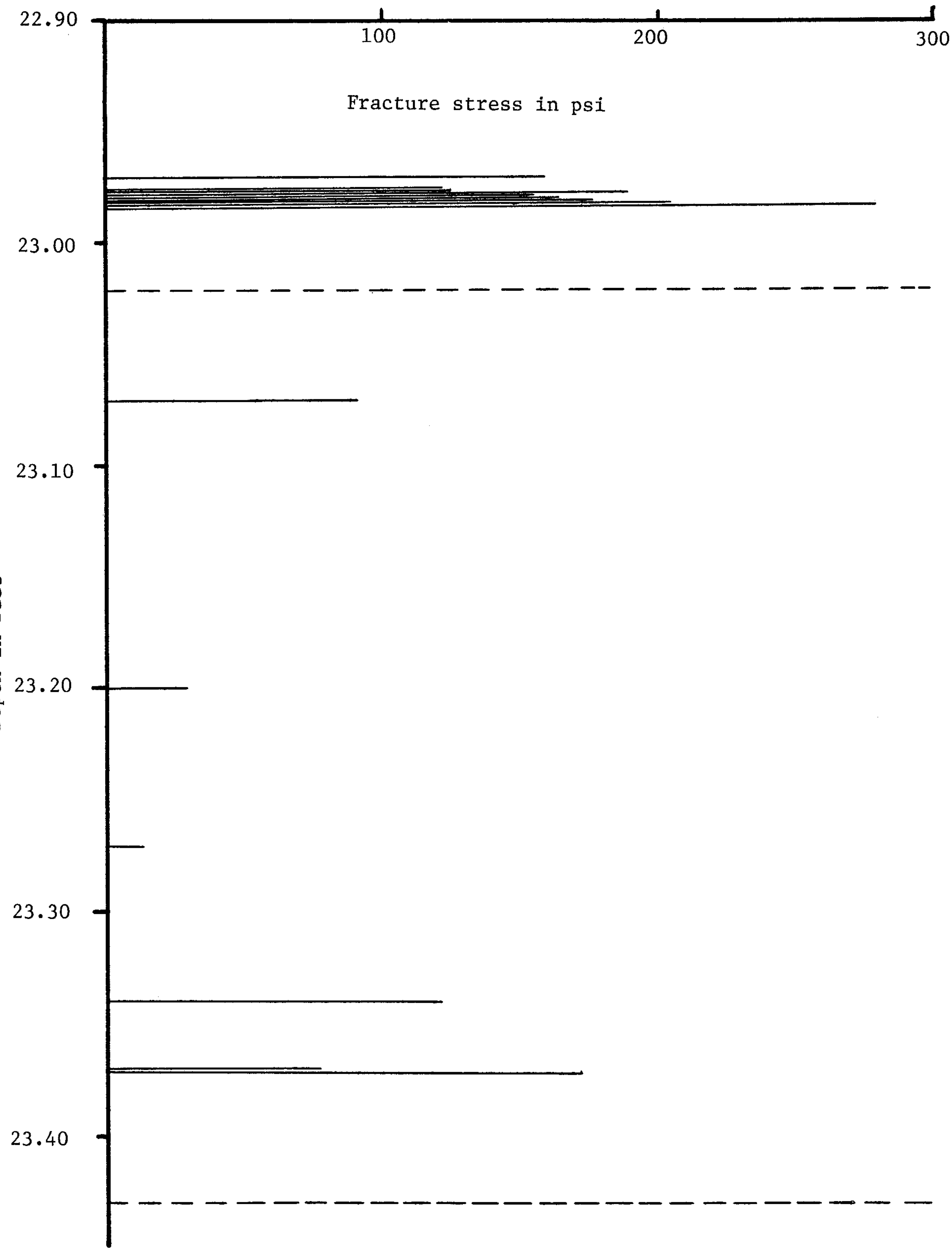


Fig. 10. Direct tensile testing of Tennessee oil shale around 23 feet depth. (Note: 1 ft = 0.305 m, 1 psi = 6.9 kN/m^2)

The indirect tensile strengths of the Tennessee oil shale are much lower than those of the Colorado oil shale (22). For direct tensile testing, most horizontal cracks in the Tennessee shale fractured below 2.8 MPa (400 psi) whereas for direct tensile testing, the Colorado samples fractured at about twice that value.

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