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Laboratory Investigation on the Effect of In Situ Stresses on Hydraulic Fracture Containment

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ABSTRACT

Laboratory experiments have been conducted to determine the effect of in situ stress variations on hydraulic fracture containment. Fractures were initiated in layered rock samples with prescribed stress variations, and fracture growth characteristics were determined as a function of stress levels. Stress contrasts of 2-3 MPa were found to be sufficient to restrict fracture growth in laboratory sam-samples of Nevada tuff and Tennessee and Nugget sandstones. The required stress level was found not to depend on mechanical rock properties. However, permeability and the resultant pore pressure effects were found to be important. Tests conducted at bimaterial interfaces between Nugget and Tennessee sandstone show that the resultant stresses set up near the interface due to the applied overburden stress affect the fracture behavior in the same way as the applied confining stresses. These results provide a guideline for determining the in situ stress contrast necessary to contain a fracture in a field treatment.

INTRODUCTION

An understanding of the factors which influence and control hydraulic fracture containment is of great importance for the successful use of hydraulic fracturing technology in the enhanced production of of natural gas from tight reservoirs. Optimally, this understanding would provide improved fracture design criteria to maximize fracture surface area in contact with the reservoir with respect to volume injected and other treatment parameters. In formations with a positive containment condition (fracturing out-of-zone is not anticipated), long penetrating fractures could be effectively used to develop the resource. For the opposite case, the options would be to (1) use a small treatment, so that large volumes are not wasted in out-of-zone fracturing, and accept a lower productivity improvement or (2) reject the zone as uneconomic. These decisions can not be made satisfactorily unless criteria for vertical fracture propagation are developed and techniques for readily measuring the important parameters are available.

Presently, both theoretical and experimental

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efforts are being pursued to determine the important parameters and their relative effects on fracture growth. Two possible modes of fracture containment are possible. One is the situation where fracture growth is terminated at a discrete interface. Examples of this include fracture termination at weak or unbonded interfaces as shown by Daneshy[1], Teufel[2], Anderson[3], and Teufel and Clark[4] in their laboratory experiments and theoretical models by Simonson _et al_[5] and Hanson _et al_[6] which predict that fracture growth will terminate at a material property interface.

The other mode may occur when the fracture propagates into the bounding layer, but extensive growth does not take place and the fracture is thus restricted. An example is the propagation of the fracture into a region having an adverse stress gradient so that continued propagation results in higher stresses on the fracture and, thus, self-limiting growth, as suggested by Simonson _et al_[5] and seen in mineback experiments[7]. Another example is the possible restriction caused by propagation into a higher modulus region where the decreased width results in increased pressure drop in the fracture which might inhibit extensive growth into that region relative to the lower modulus region. Other parameters, such as natural fractures, treatment parameters, pore pressure, etc.[6,8] may affect either of these modes.

Laboratory[1,2,3,4] and mineback experiments[7] have shown that weak interfaces and in situ stress differences are the most likely factors to contain the fracture and weak interfaces are probably effective only at shallow depths. Thus, the present experiments are being performed to determine the effect of in situ stresses on fracture containment, both in a uniform rock sample and at material property interfaces. Quantitative data on the levels of in situ stress necessary to restrict fracture growth in different rock types have not previously been available and are determined here. This work is an extension of mineback experiments conducted at DOE's Nevada Test Site which showed that in situ stress differences of 2 MPa were sufficient to restrict the growth of hydraulic fractures in ash-fall tuff whereas material property differences of factors of 5 to 15 did not contain the fracture[6].

Finite element calculations in the present work can give the stress distribution in the lab samples, and the observed fracture extent can be correlated with specific stress levels. These calculations also show that in situ stress differences may occur in layered specimens under an overburden load and tests must be carefully constructed to ascertain that one is evaluating only the effects of the desired parameters. The unique feature of these studies is that the actual stresses, whether applied directly or resulting indirectly from the layering and the overburden pressure, are correlated with the degree of fracture penetration in various rocks.

EXPERIMENTAL PROCEDURE

These experiments were conducted with Tennessee sandstone, Nugget sandstone and also ash-fall tuff for comparison with mineback experiments. Properties of these rocks are shown in Table 1. Interfaces between the Tennessee and Nugget sandstones have a Young's modulus contrast of a factor of 1.5 whereas the Young's modulus of ash fall-tuff is significantly lower than both sandstones. These rocks are cut and ground into 20 cm diameter cylinders of either 10 cm or 20 cm length. The 20 cm length samples are used for tests of a single rock type with no interface. The 10 cm length samples can be stacked so that a material property interface can be obtained. No bonding is used since frictional properties of the rock are sufficient to cause the fractures to propagate across interfaces with the overburden pressures used in these tests. A 1.90 cm diameter hole is drilled 5.72 cm into the top of the specimen and an aluminum casing is epoxied in the hole. A 1.27 cm hole is drilled 2.54 cm farther, and this is the zone (open hole) where the hydraulic fractures are initiated. Figure 1 shows a diagram of the test configuration.

The sample is placed in a load frame which is capable of supplying up to 28 MPa overburden stress for the given sample size. Specially fabricated cylindrical bladders are used to provide lateral confining pressures up to 8 MPa. These bladders, which can be pressurized by hydraulic fluid, consist of copper sleeves sealed inside of steel rings with a narrow annular spacing. The copper bladder is inflated against the sample to provide the required stress. The bladders are slightly less than 10 cm long and can be used to supply the lateral confining stress to only one half of the specimen. The other half may be left unconfined or stressed with a second bladder. Thus, differential stress states can be created even in homogeneous samples and each half of the layered specimens can have prescribed contrasts in both in situ stress states and mechanical properties across the layer interface.

A servo-controlled pump system maintains constant fluid flow rates from 0 to over 100 cm^3/sec and pressures up to 70 MPa. The fracture fluid is either dyed water or 40 weight motor oil which is displaced by the hydraulic fluid of the pump system. A 120 cm^3 reservoir of frac fluid is situated somewhat above the wellbore collar so that large amounts of the fluid are available for fracturing. Most tests are conducted at flow rates of 0.1 to 5 cm^3/sec.

A photograph of the apparatus and samples is shown in Figure 2. To minimize end effects, the actual specimen to be tested is situated between oversized blocks of the same material. The fluid reservoir can be seen on the left side. The ring on the lower half sample is the bladder which provides the lateral stress.

Both digital and analog recordings of the borehole pressure are made during an experiment. These records are analyzed for indications of whether the rock behaved normally and a valid test was conducted. When the fracture has broken through the sample, the specimen is split, examined and photographed.

FINITE ELEMENT CALCULATIONS

The stress state in the specimens under the various loading conditions was calculated using a finite element code (Automatic Dynamic Incremental Non-linear Analysis--ADINA[9]), developed at MIT. This program solves linear and nonlinear, static and dynamic stress analyses, for solids, structures and fluidstructure systems. For the present effort, it is used in two capacities. First, at a bimaterial interface under overburden load, it is well known that a differential stress state will develop due to the difference in properties. ADINA is used to determine what the stress state is and its significance to the experiments. For example, under certain specified loading conditions, a fracture may be terminated at the interface because of large differential stress rather than any material property effect as it might appear. Second, stress contours in the specimens can be determined so that fracture extent can be compared to stress levels within a specimen, allowing inference of critical stress levels for fracture containment.

RESULTS

(A)

The results of the fractures conducted in tuff were used for comparison with results of mineback experiments[7] which showed that a stress increase of 2 MPa was sufficient to terminate fracture growth. These tests were conducted using full 20 cm length samples and several confining pressures on either top and bottom. The overburden stress was 2.76 MPa. Usually, 30 to 50 cc of dyed water were injected at flow rates of 1.6 cc/sec.

Several unconfined tests were conducted to provide a base case on which to compare and evaluate the effect of confining pressure. In general, these unconfined tests resulted in fractures which were penny-shaped and centered around the open-hole zone, except near the edge of the sample where boundary effects were obviously significant. This boundary zone was typically 1 to 2 cm wide.

After the unconfined tests, lateral confining pressures of 1.38 and 2.07 MPa were applied to either the top or bottom half of the tuff samples. Samples were compared with finite element calculations of stress profiles to determine the effect of the confining stress. For the 1.38 MPa confining pressure case, only a marginal difference in fracture growth was observed. However, for the 2.07 MPa confining stress case, the normal fracture growth pattern had been significantly altered. Figure 3 shows a photograph of two tuff samples, one with 2.07 MPa confining pressure above and the other with 2.07 MPa confining pressure below. Figure 4 shows a schematic of these results and the stress contours calculated with the finite element code. These fracture geometries are in marked difference to a penny-shaped fracture. Fracture growth here is predominantly away from the high stress region, and it appears to terminate at a stress level of from 1.4 to 2.0 MPa. This is in excellent agreement with mineback results.

(B)

The same type of procedure was conducted using Nugget sandstone samples. Full 20 cm length samples were used with overburden stresses of either 5.5 MPa or 20.7 MPa and several confining stresses up to 4.83 MPa on either top or bottom. Typically 40-120 cm^3 of fluid was injected.

The first series of tests used dyed water at flow rates from 0.5-3 cm^3/sec and overburden stresses of 5.5 MPa. Confining stresses of 3.45 and 4.83 were applied on top or bottom. The results showed no obvious effect at 3.45 MPa and only a marginal effect at 4.83 MPa confining stress. However, the fluid leakoff, particularly along the bedding, was excessive, and the resultant pore pressure effects may have influenced the results.

A second set of tests using a 40 weight motor oil as the fracture fluid at 0.5 cc/sec injection rate was subsequently conducted in the Nugget. Overburden stress was 20.7 MPa and confining stresses of 0, 1.72 and 3.45 MPa were applied. In these cases, fluid leakoff was considerably less, although still significantly more than in tuff or Tennessee sandstone. The results here were more conclusive. A confining stress of 3.45 MPa restricted fracture growth whereas the 1.72 MPa confining stress case was similar to zero stress. Thus, 2-3 MPa stress was necessary for significant fracture containment.

(C)

For the Tennessee sandstone, half block samples were used so that step changes in "in situ" stress could be applied. This was performed by applying the lateral confining stress to either the top or bottom half before applying the overburden. Note that if the overburden stress was applied first and then the lateral stress, a smooth gradient of stress would occur across the interface rather than a discontinuous one. Overburden loads of 20.7 MPa were used so that sufficient friction at the interfaces would exist to allow the fractures to cross. Confining stresses of 0, 1.72, 3.45, and 6.89 MPa were applied. The fracture fluid was dyed water, injected at 0.5 cm^3/sec for most tests.

Figure 5 shows a photograph of three separate tests. The block on the left had a 6.89 MPa lateral confining stress on the bottom, the middle block had zero lateral stress and the right specimen had 6.89 MPa lateral stress on top. The direction of propagation is away from the region of high stress. Note that the case with the stress on top still results in a fracture in the top half because the fracture initiated there and there are no stress gradients. Thus the fracture will propagate as normal in this uniform stress field until it breaks across the interface and feels the effect of the reduced stress state. (Recall that a discontinuous drop in stress occurs at the interface for this case.)

Figure 6 shows a photograph of a series of tests run at four different confining stresses on the bottom half block--0, 1.72, 3.45, and 6.89 MPa. The fracture growth downwards is a monotonically decreasing function of the stress magnitude. In Figure 7, the fracture penetration across the interface is plotted as a function of lateral confining stress. The point where the effect of the in situ stresses becomes significant is about 2 MPa.

(D)

A fourth set of experiments examined fracture growth near a material property interface. Tests were conducted on half blocks of Tennessee stacked on top of Nugget sandstone or the reverse case. Overburden stresses of 20.7 MPa were applied with no confining stresses. Fractures initiated in the Tennessee sandstone used dyed water at 0.5 cc/sec. Fractures initiated in the Nugget used oil at 0.5 cc/sec.

Figure 8 shows a comparison of the two cases. Fractures penetrated farther in the Tennessee even though the modulus is significantly higher than in the Nugget. This can be attributed to the state of stress induced in the sample due to the low Poisson's ratio and high Young's modulus of the Tennessee sandstone relative to the Nugget rather than the direct effect of the property differences. When overburden stresses are applied this results in tension in the radial and tangential directions in the Tennessee and compression in the Nugget. Thus fracturing is enhanced in the Tennessee due to the lower stress. The amount of penetration of the fracture from the Tennessee into the Nugget in the right sample is approximately equivalent to that observed in the case of 3.45 MPa confining pressure in the Nugget tests or 1.72 MPa step function confining pressure in the Tennessee tests (Figure 6).

Finite element calculations in Figure 9 show the calculated stress distribution in the samples for the overburden stress of 20.7 MPa. For the case of a fracture in Tennessee sandstone propagating towards the Nugget sandstone, a stress level of 1.5 - 2.0 MPa is realized at the interface. The stress distribution through an arbitrary cross section, A-A', is also shown (compression is positive). In the other case the low stress in the Tennessee sandstone results in fracture growth similar to the results in Figure 5.

DISCUSSION

(A)

The results presented here show the effect of in situ stress variations on fracture growth in laboratory samples. In general, it has been found that a 2-3 MPa change in stress is sufficient to restrict fracture growth into the higher stress region for three different rock types. This is in good agreement with small scale field tests conducted in tuff and mined back at DOE's Nevada Test Site[7]. It should be remembered, however, that the amount in which a high stress region restricts fracture growth depends on many parameters. If there are large pressure increases during a fracture treatment, fracturing into a higher stress bounding layer may actually be the path of least resistance for a given fluid volume compared to, say, enduring the significant pressure drops down the length of a long fracture. Fracture length, apparent viscosity, flow rate and rock properties must all be considered when trying to determine if a fracture will be contained or not. However, it is believed that these results give some guidance to the level of stress in the bounding layers which is necessary to restrict vertical, out-of-zone fracturing.

Apparently, the level of stress necessary to contain a fracture is not strongly affected by mechanical rock properties. Little difference was observed for Nevada tuff and Tennessee sandstone, which are significantly different rocks. However, the permeability of the formation may be very significant, as exhibited in the Nugget sandstone samples fractured with water. The high leakoff rates possibly resulted in high pore pressures near the fracture and, thus, reduced effective stresses. This may have negated to some degree the applied stress differences. When more viscous fluids were used, the results became similar to the tuff and Tennessee sandstone.

The results of the bimaterial tests are presented to show the effect of in situ stresses in less obvious situations. Laboratory experiments[1,2,3,4], mineback experiments[7], and occasional field evidence (e.g., ref. 12) have shown that a material property interface will not contain a hydraulic fracture. However, there are also much field data (e.g., ref. 13) which suggest that the effect of a bounding layer often contains hydraulic fractures. The results of the bimaterial tests shown in Figures 9 and 10 illustrate how, under proper loading conditions, differences in elastic moduli between successive layers may result in stress differences that either enhance or deter fracture growth into the bounding, non-reservoir strata. These contrasts in stress may be ubiquitous in the field, but our lack of understanding of the loading conditions (e.g., tectonics, boundary conditions and mechanical properties) precludes quantitative prediction of stress states at this time. Thus, containment of a fracture may often occur at a material property interface because the bounding layer is a higher stress region rather than any direct material property effects; but our knowledge of the stress distribution at depth is usually poor so this is never correlated.

(B)

The results of the applied lateral stress on fracture pressure has also been studied using the results of these tests. Figure 10 shows the breakdown pressure observed in the three rock types for various confining stresses. For a very long borehole the breakdown pressure should be influenced by the stresses according to the equation[10,11]

$$P_c = 3\sigma_{min} - \sigma_{max} + \sigma_t \tag{1}$$

where, P_c is the breakdown pressure, σ_t is the tensile strength, and σ_{min} and σ_{max} are the principal horizontal stresses around the borehole which are equal in these tests. Then

$$P_c = 2\sigma_{confining} + \sigma_t \tag{2}$$

and the slope of the curve in Figure 10 should be 2. This is the case for Nugget and Tennessee sandstones despite the short open-hole section in the sample, but the tuff deviates somewhat. The breakdown pressures for the Nugget are higher than for the Tennessee even though the Nugget's tensile strength is less. Further, the intercept at zero confining stress, which should be the tensile strength, is a factor of 3-4 too high. It appears that although the general relation between stress and breakdown pressure is verified, the value of the tensile strength to be used is a problem. This is probably due mainly to pore pressure effects--the high permeability Nugget shows a greater deviation--but borehole size effects, the low aspect ratio of the borehole and the epoxied casing may also contribute in these experiments.

(C)

The primary advantage of laboratory experiments over field measurements and observations (including mineback) is that the important parameters can be well controlled. If the proper rock types can be obtained, it is posible to test fracture growth near material property interfaces with wide varieties of contrasts. Also, the level of stresses applied, characteristics of the interfaces, etc., can be tailored for the specific tests. On the other hand, there are also many drawbacks which may significantly affect the results and yet are usually overlooked.

The most obvious problem is that of sample size.

Clearly the boundaries affect the results by providing a free surface. Fracture mechanics principles show that the fracture approaching a free surface will require less pressure to advance the crack. The distances over which such effects become important are not easily determined, and thus, the effect on the tests is largely surmised. In the present experiments, the effect of the free surface is dramatic at least 1-2 cm from the boundary.

Secondly, dynamic effects may produce results much different from those obtained in quasi-static tests. A dynamic effect, for example, is the fracturing of the rock sample from the borehole to the boundary in a single burst. This probably occurs near the terminal crack velocity of the rock which is a significant fraction of the characteristic velocities (i.e., compressional, shear, Rayleigh wave). This most likely negates any effect of fluid pressure in the crack since the fluid penetration rate will be much lower. In a hydraulic fracture treatment in the field, however, the direction of fracture propagation is a complex feedback process where information is carried from the extremities of the fracture to the borehole and back out to the extremities through the fluid. There must be a small interval of time before the effects of differences in stress or material properties are "recognized" and a "decision" is made as to the direction of propagation which should occur in the fracture as a whole. Such a feedback process, therefore, cannot take place when the fracturing in a rock block occurs in a single dynamic burst. These dynamic effects appear to be more prevalent in small size blocks or in high Young's modulus, high strength rock samples. Increasing sample size or decreasing the elastic modulus/strength may alleviate the problem. If not, the results from the test may be misconstrued. Usually, this can be easily recognized from the observation of the pressure record. Typically a large breakdown pressure is required and then the pressure immediately drops to a low value. No further fracturing occurs, but flow through the fracture keeps the pressure slightly elevated. The present tests were carefully designed and monitored to avoid this problem wherever possible.

As seen in the finite element calculations, the overburden stress, as well as the applied confining stress, results in a distribution of horizontal stress which is not known a priori. It should also be noted that for the tests with a discrete interface (both single material or bimaterial interface) the order in which the stresses are applied will affect the final stress distribution. If the overburden is applied first, the sample behaves like a well-bonded interface; that is, the confining stresses will be transmitted in some degree to the other half block. If the confining stresses are applied first, the stressed block will have a constant confining stress throughout it with the resultant stresses due to application of the overburden stress superposed on it. Note that if both blocks are the same material, this results in a step change in stress across the interface. A unique feature of these experiments is the emphasis of the effects of the actual stress in the sample, whether that stress is applied directly or results indirectly from the layering and the overburden pressure.

(D)

Finally, development and use of an in situ stress containment criterion will depend upon our knowledge of the stress state at depth. Since practical techniques for obtaining detailed in situ stress measurements in a borehole are not likely to be developed in the near future, prediction of the stress distribution from indirect measurement of formation properties in a basin is important. A highly likely cause of stress changes with depth is due to gravity loading of the varied-property strata. This may be altered by tectonics, diagenesis, creep, etc., but the general stress distribution may be predictable. One of the most beneficial possibilities is where shale creeps over time periods sufficient to cause it to be essentially hydrostatic. How this would effect the nearby sand lenses or strata that may not creep as readily is unknown, but quite possibly the shales would have a higher stress state and act to contain the fractures. Our knowledge of the lithosphere's state of stress is essential in order to successfully stimulate the unconventional gas reservoirs.

CONCLUSIONS

Laboratory experiments have shown that a 2-3 MPa contrast in in situ stress across adjacent rock strata is sufficient to restrict the growth of a hydraulic fracture for the rock types tested in these experiments. Mechanical properties of the rock were not found to affect significantly the required stress level; however, pore pressure effects appear to be very important.

These experiments have shown that a bimaterial interface under the proper loading conditions may also result in stress contrasts sufficient to contain fractures. This is likely to be a situation encountered often in the field.

A stress ring has been developed which has proven useful for conducting confined fracture tests in the lab. This ring enables stress contrasts to be applied easily to layered rock samples.

Breakdown pressures were found to agree well with their expected trend as a function of confining stress. However, pore pressure effects and probably borehole size and geometry effects resulted in pressures that were significantly larger than would be expected from the tensile strength.

Finally, these findings indicate that a method for practically determining the in situ stress state at depth in a wellbore must be developed if the unconventional reservoirs are to be treated successfully. Knowledge of stress variations would be an important aid in fracture design and economic decisions.

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Table I

Rock Properties

Type	Young's Modulus	Poisson's Ratio	Tensile Strength	Permeability
Tennessee sandstone	49.5 GPa*	0.08*	12.0 MPa	$0.01 \times 10^{-3}\ \mu m^2$
Nugget sandstone	33.6 GPa*	0.16*	6.9 MPa	$0.27 \times 10^{-3}\ \mu m^2$
Tuff	8.3 GPa**	0.15**	3.1 MPa**	$0.01 \times 10^{-3}\ \mu m^2$

*Measured in uniaxial compression

**Measured from direct pull tension tests

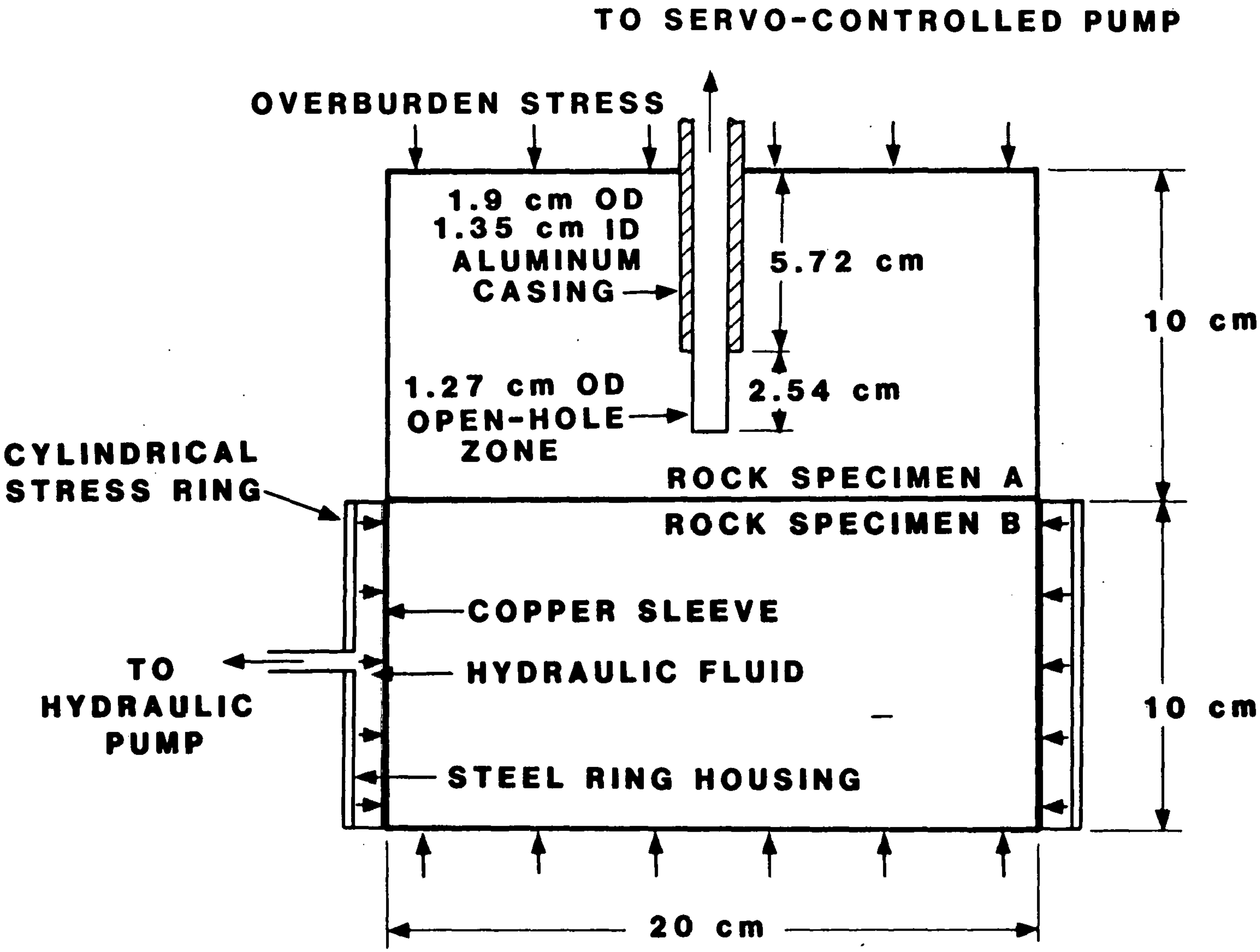

Figure 1. Configuration of Cylindrical Samples, Casing and Stress Ring.

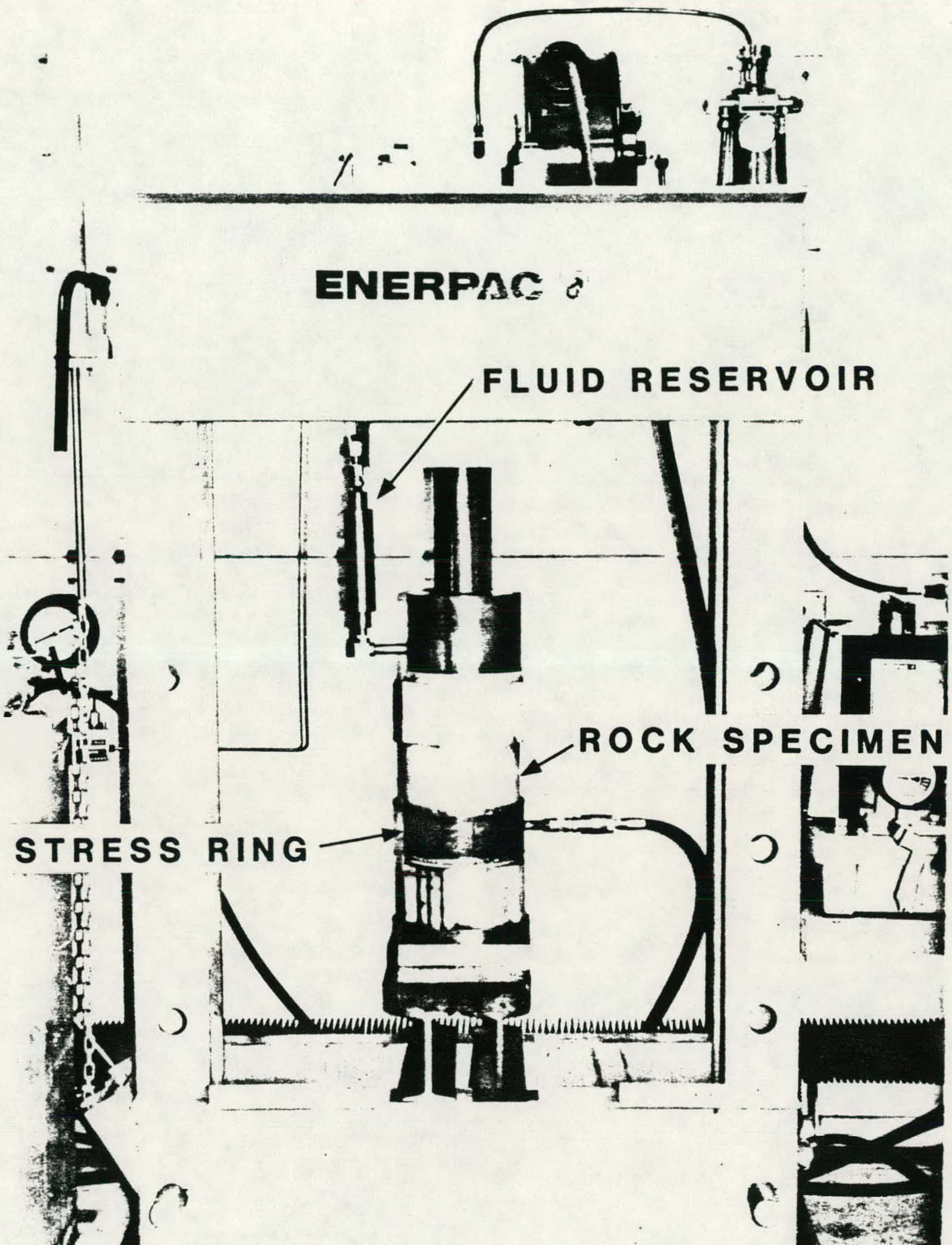

Figure 2. Photograph of Apparatus.

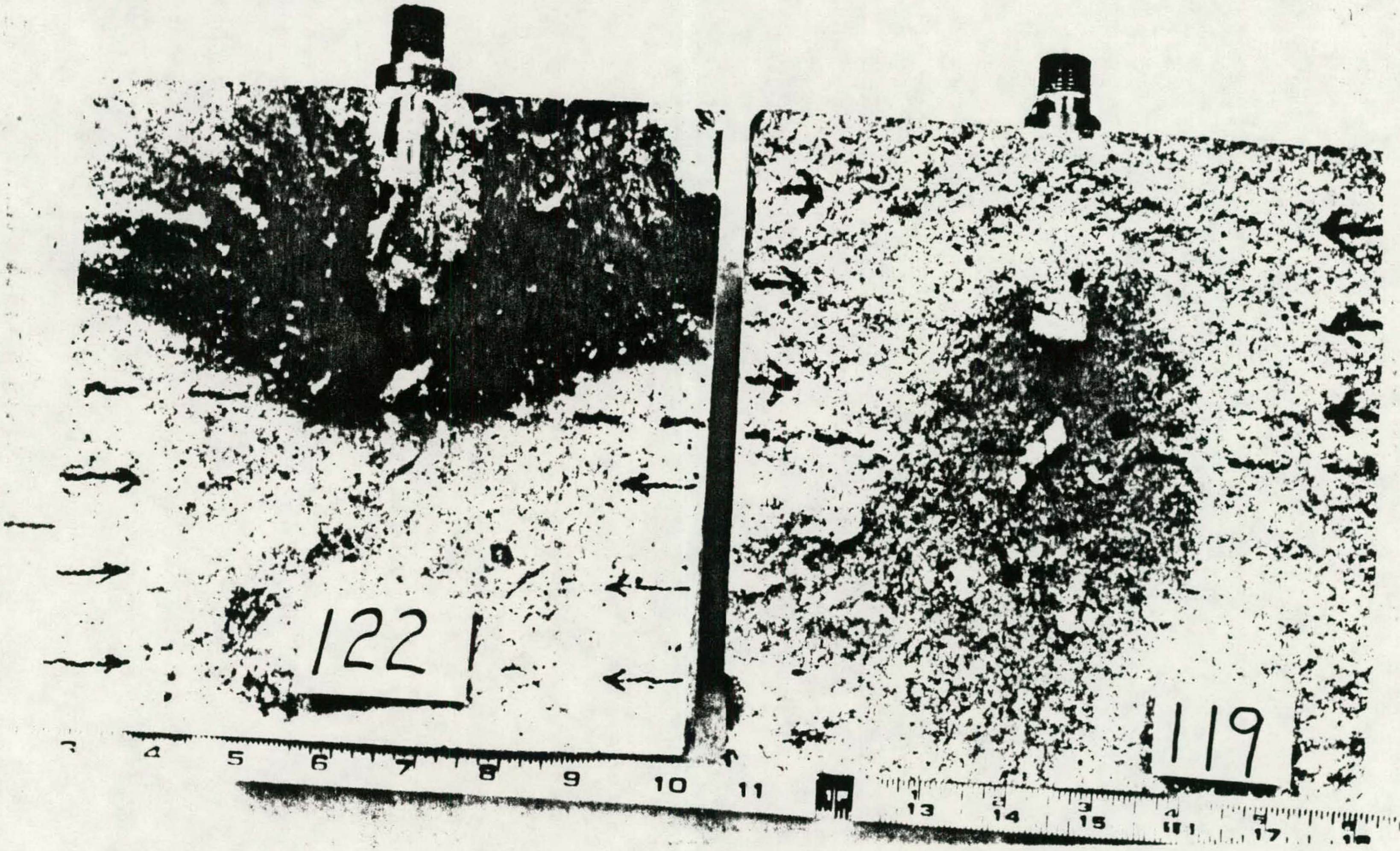

Figure 3. Effect of 2.07 MPa Confining Pressure on Bottom (Left) and Top in Tuff Samples.

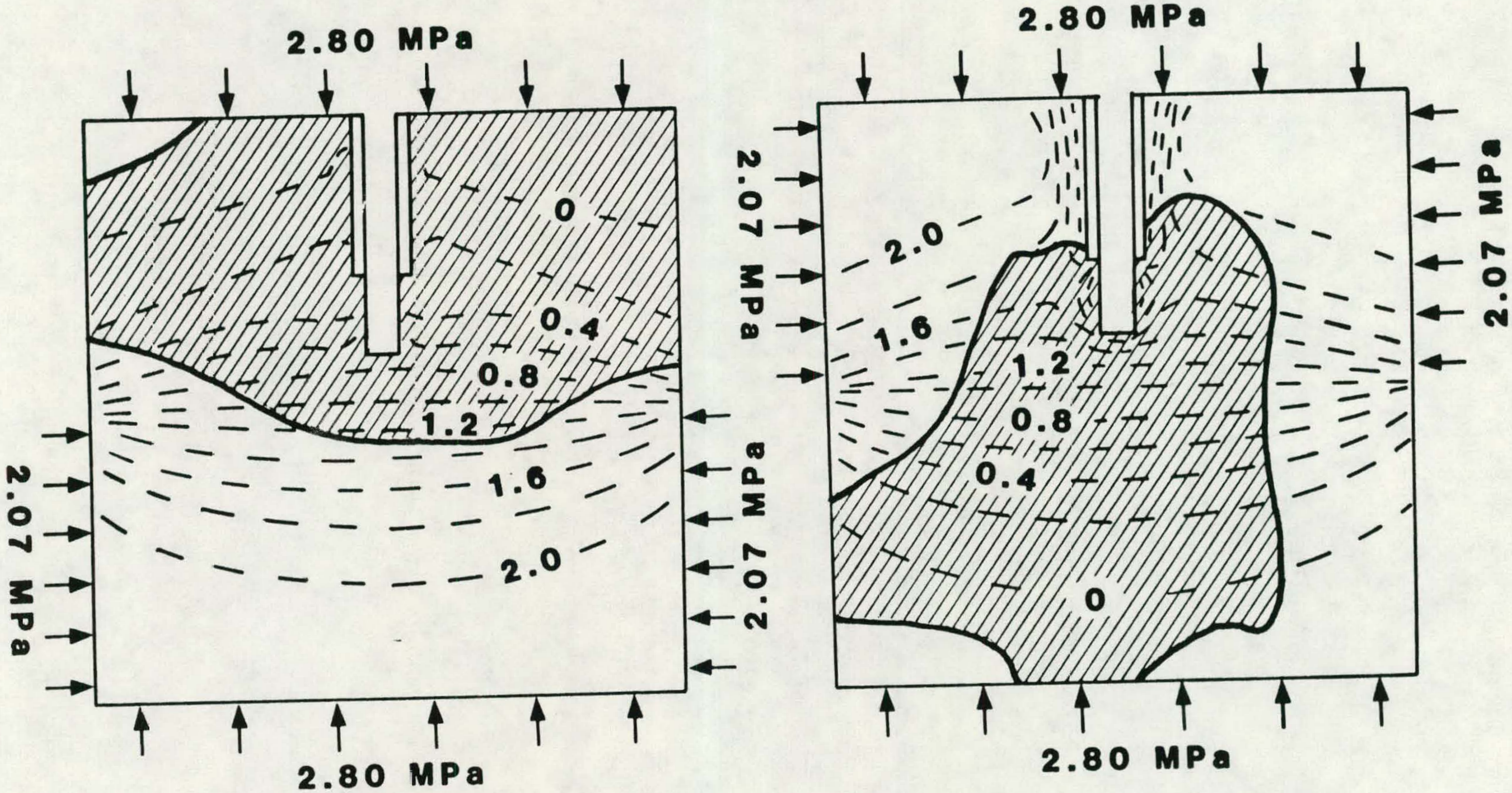

Figure 4. Finite Element Calculation of Stress Levels in Tuff Compared to Observed Fracture Geometry.

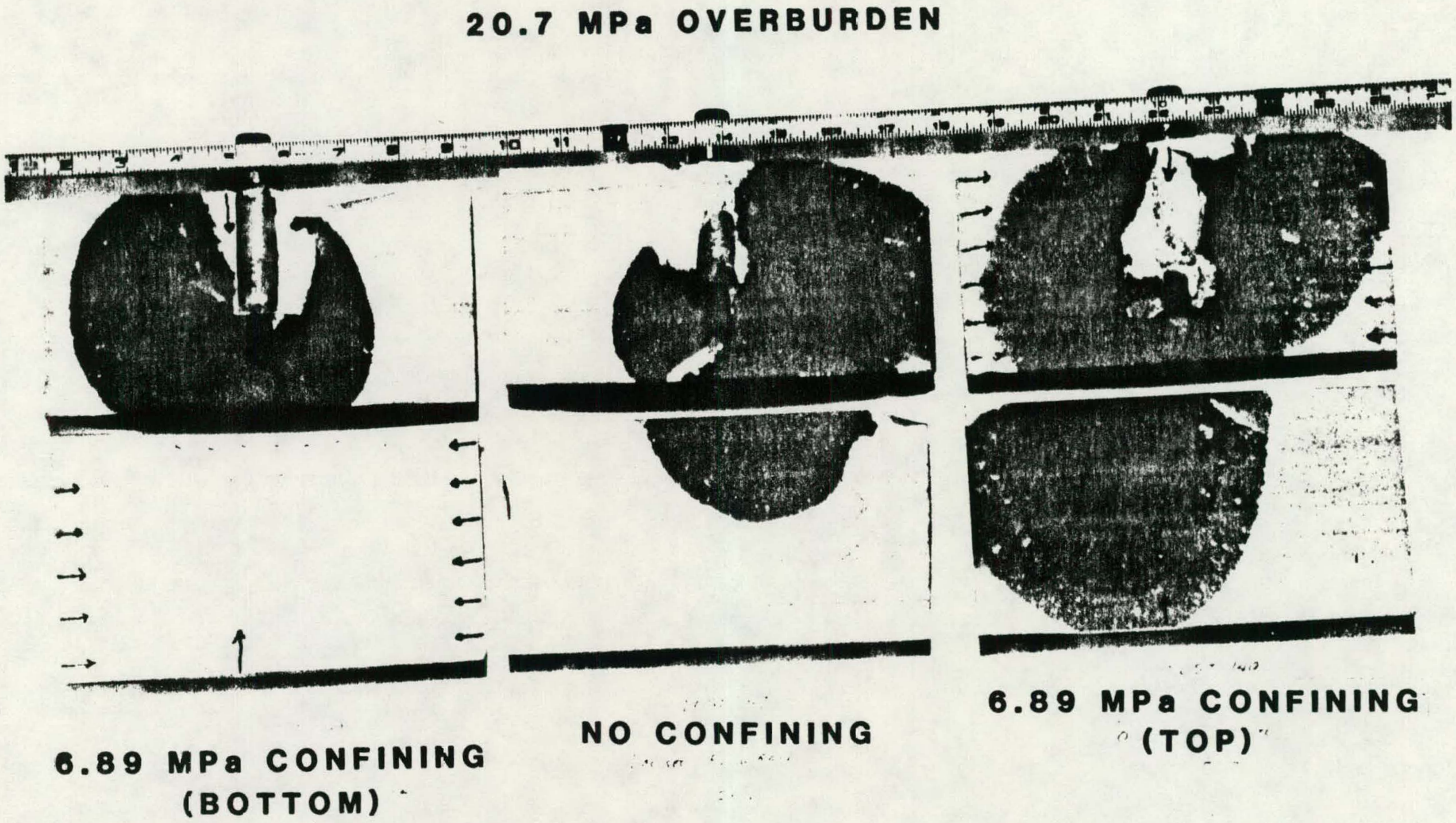

Figure 5. Effect of 6.89 MPa Confining Pressure on Tennessee Sandstone Samples.

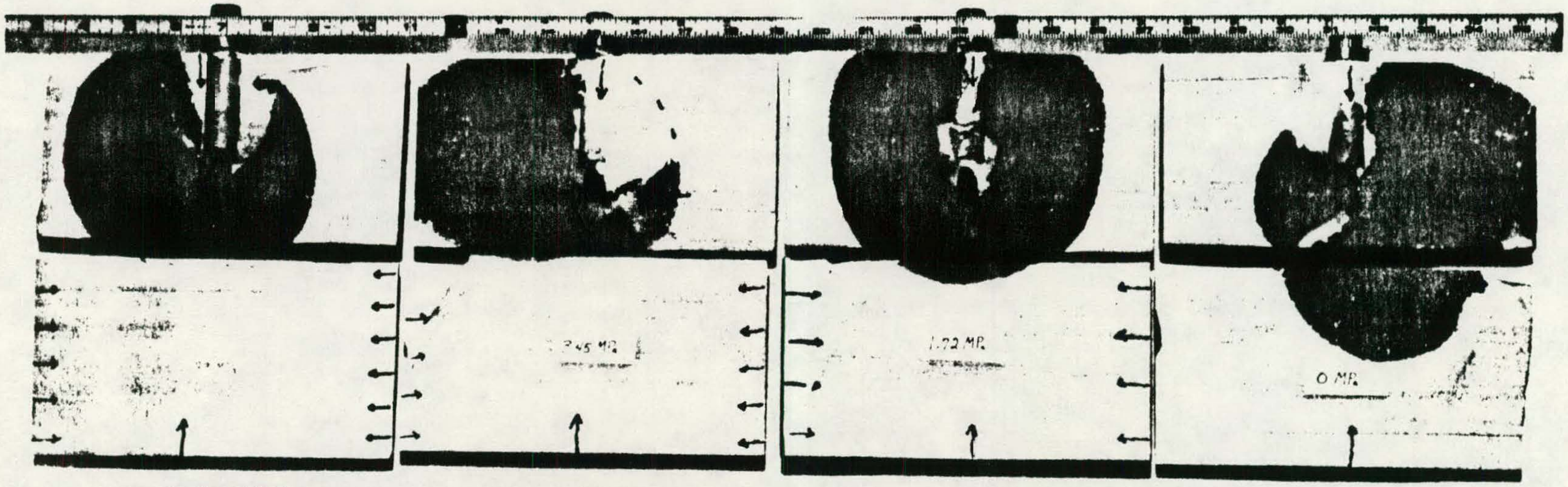

Figure 6. Effect of Four Confining Pressures on Tennessee Sandstone Samples.

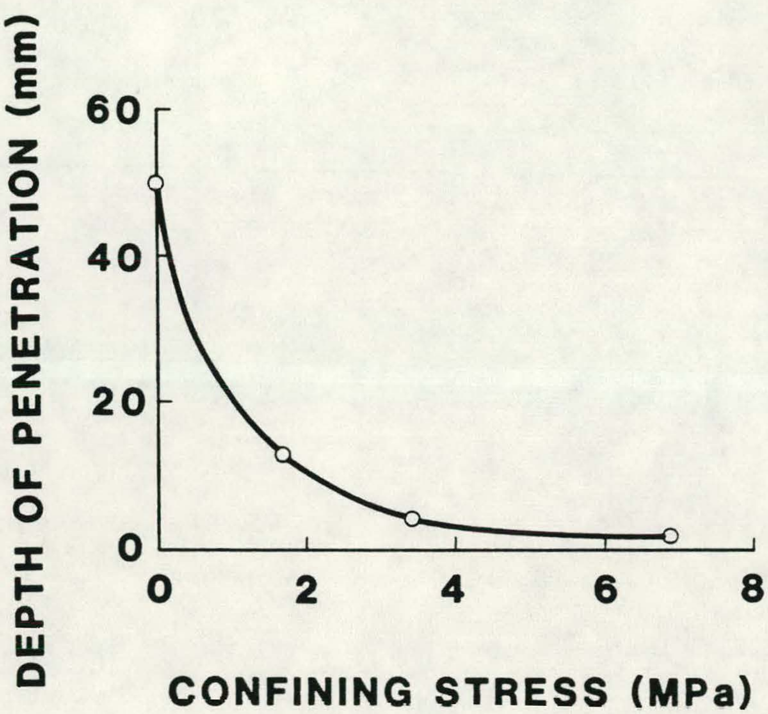

Figure 7. Depth of Fracture Penetration into High Stress Region for Tennessee Sandstone Samples.

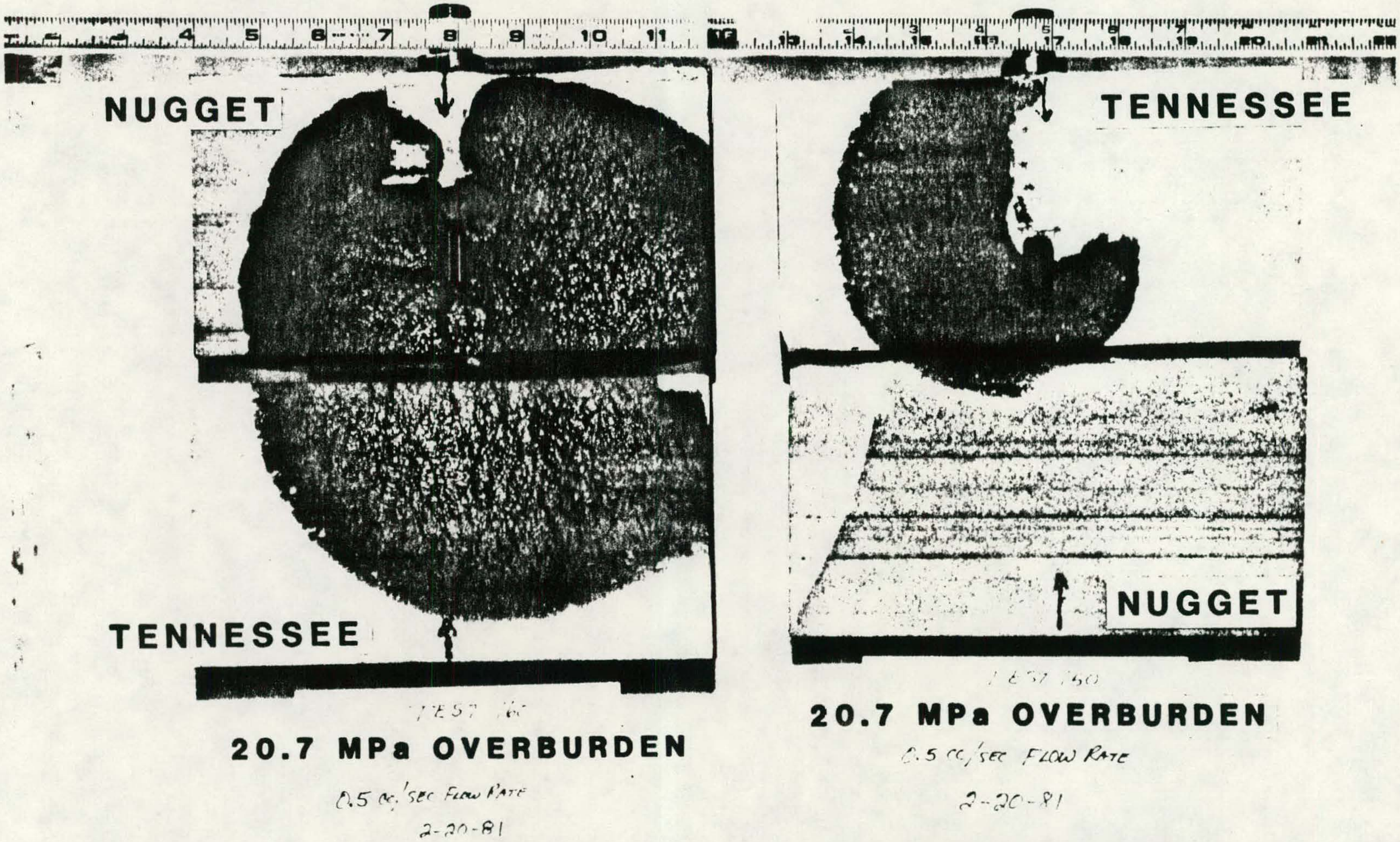

Figure 8. Fracture Behavior at a Bimaterial Interface Showing Effect of Stress Gradients Due to Overburden Loading.

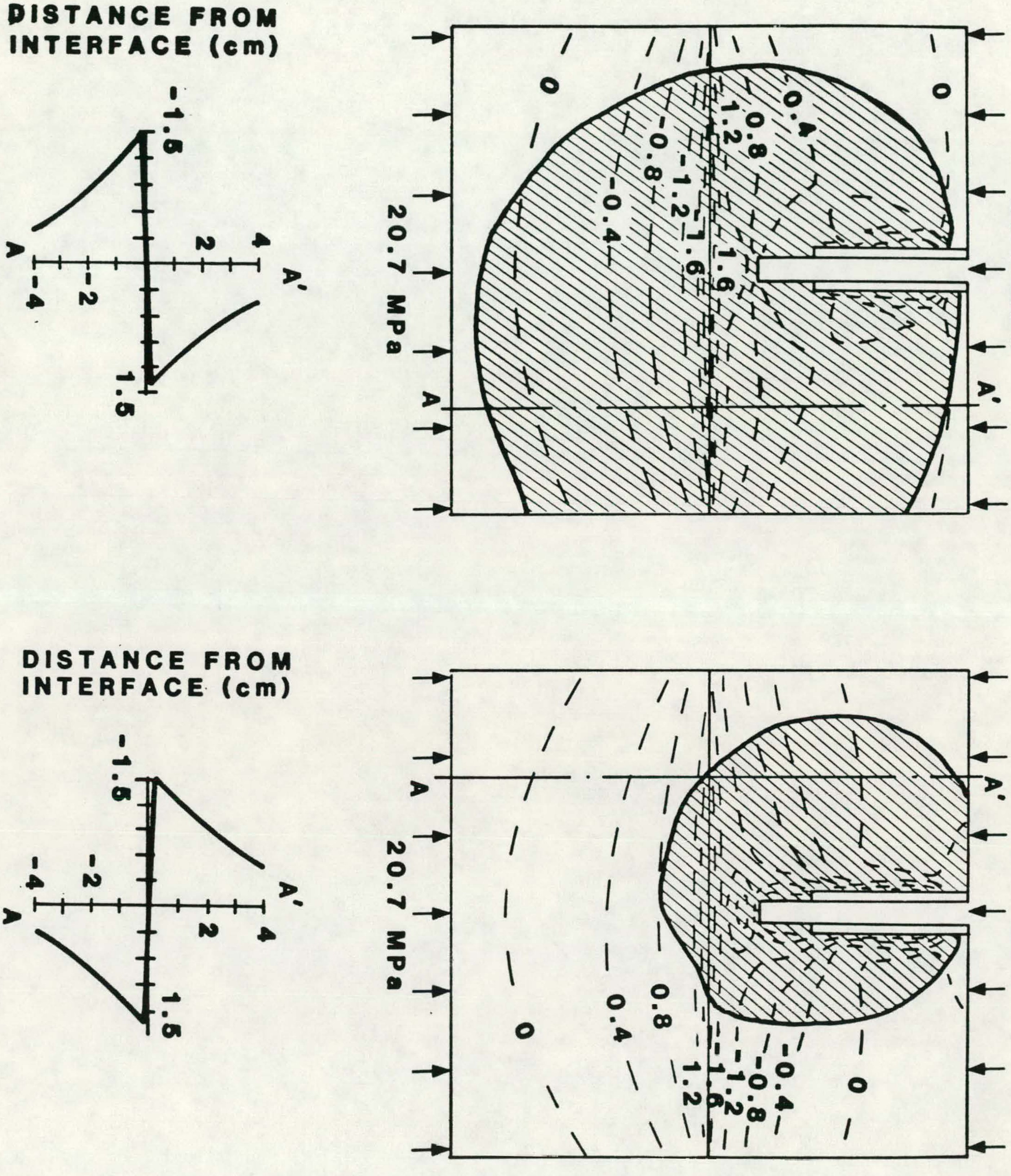

Figure 9. Finite Element Calculations of Stress Levels for Tennessee-Nugget Samples under 20.7 MPa Overburden (compression is positive).

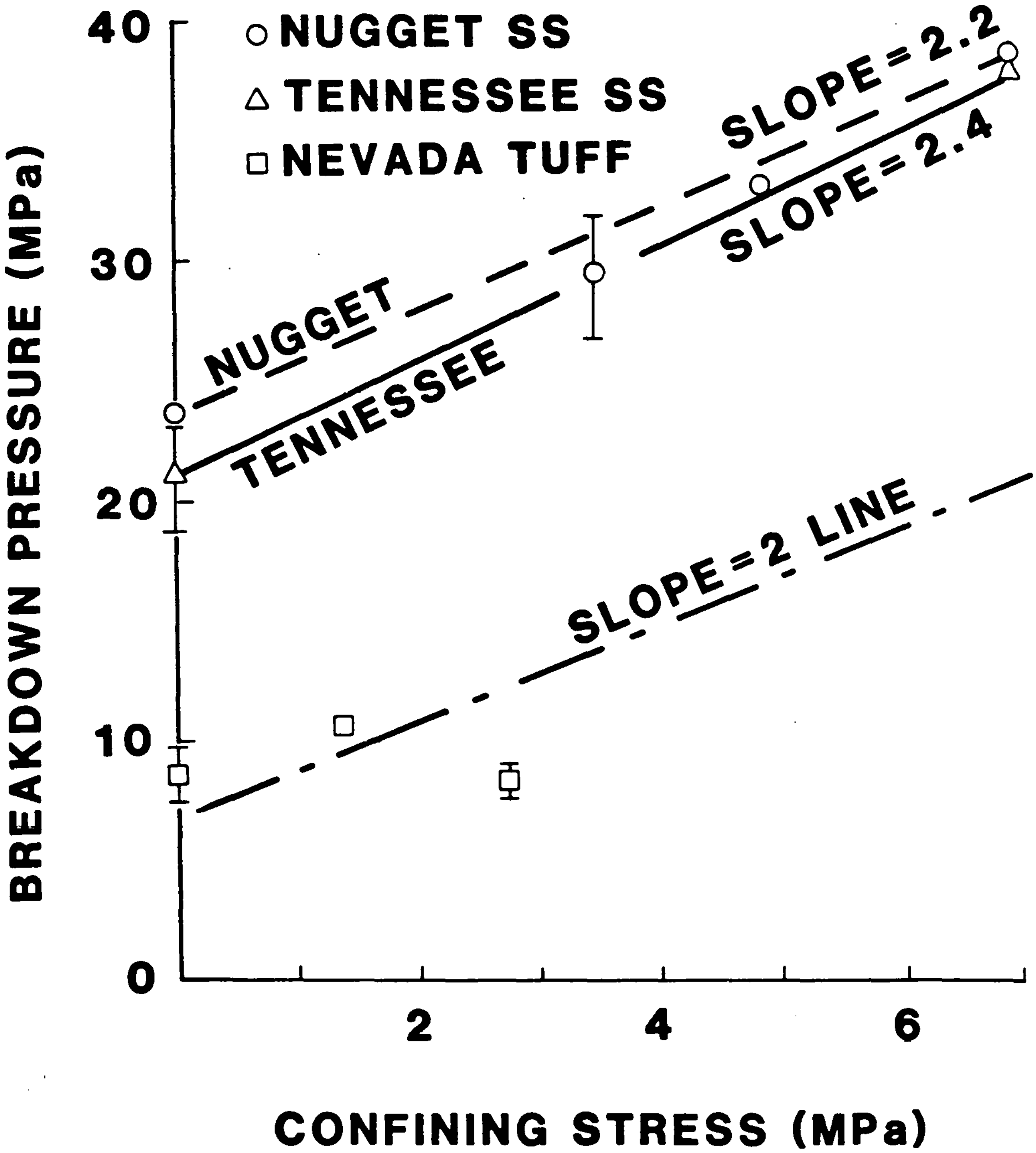

Figure 10. Breakdown Pressure vs. Confining Stress.