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Abstract

A criterion for assessing the location of crack initiation in hydraulic fracturing experiments is developed. This criterion (Ω) can be evaluated from the pressure-time records of a hydraulic fracture test. Alternatively, Ω may be estimated prior to testing if the approximate magnitude of the in-situ stress field is known and laboratory or field petrophysical data on the rock under test are available. Prior knowledge of Ω allows an upper limit on the pressure differential existing between the packers and the test section of the hydraulic fracture tool to be calculated. Provided this pressure differential (Δp) is not exceeded, crack initiation can be expected to occur in the test section, which simplifies the analysis of the hydraulic fracture data.

The results from 9 hydraulic fracture tests made at three sites in Australia have been used to test the veracity of the criterion. It has been found that the criterion readily distinguishes between the tests in which cracks occurred in the test section and those tests in which cracking initiated under the packers. The results of these analyses suggest that, as predicted by the theory, cracks initiate in the test section when $\Omega - \Delta p > 0$ MPa and under the packers when $\Omega - \Delta p < 0$ MPa.

1. Introduction

The hydraulic fracturing technique for in-situ stress measurement involves the creation and subsequent manipulation of a vertical crack in the wall of a borehole. This crack is produced by the application of a fluid pressure to a discrete portion of the borehole, termed the test section or test horizon. The isolation of this test section from the remainder of the borehole is accomplished for the duration of the testing by the juxtaposition of pressurised sealing devices called packers on either side of the test section (see Figure 1).

The details of how a particular hydraulic fracture stress measurement test is conducted depend not only upon the type of equipment being used and the nature of the rock to be tested but also to an important extent upon the judgements of the operators. The operational details that we discuss in this Record are therefore limited to the BMR's hydrofracture system and its deployment in granitic terrains. Further information about the system and its operation can be found in Chopra and Enever (1987).

In a typical hydraulic fracture test with the BMR hydrofracture system, the test section is first isolated from the remainder of the borehole by pressurising the sealing packers to 5-7 MPa. The pressure in the test section is then slowly increased until leaking of fluid past the packers is detected by the down-hole flow-meter in the hydrofracture tool. The pressure in the test section is then allowed to subside slightly until this leaking stops. The difference between this final test section pressure and that in the sealing packers is termed the pressure differential, Δp. The magnitude of Δp is an indication of the smoothness and integrity of the borehole wall and tends to be more or less independent of the absolute pressures applied to the packers and test section prior to crack initiation.

The basic tenet upon which hydrofracture testing is based is that, all other things being equal, a crack will tend to initiate in the test section where the rock is exposed to the direct action of the fluid rather than under the packers where it is not. In this view, the preference for crack nucleation in the test section allows the

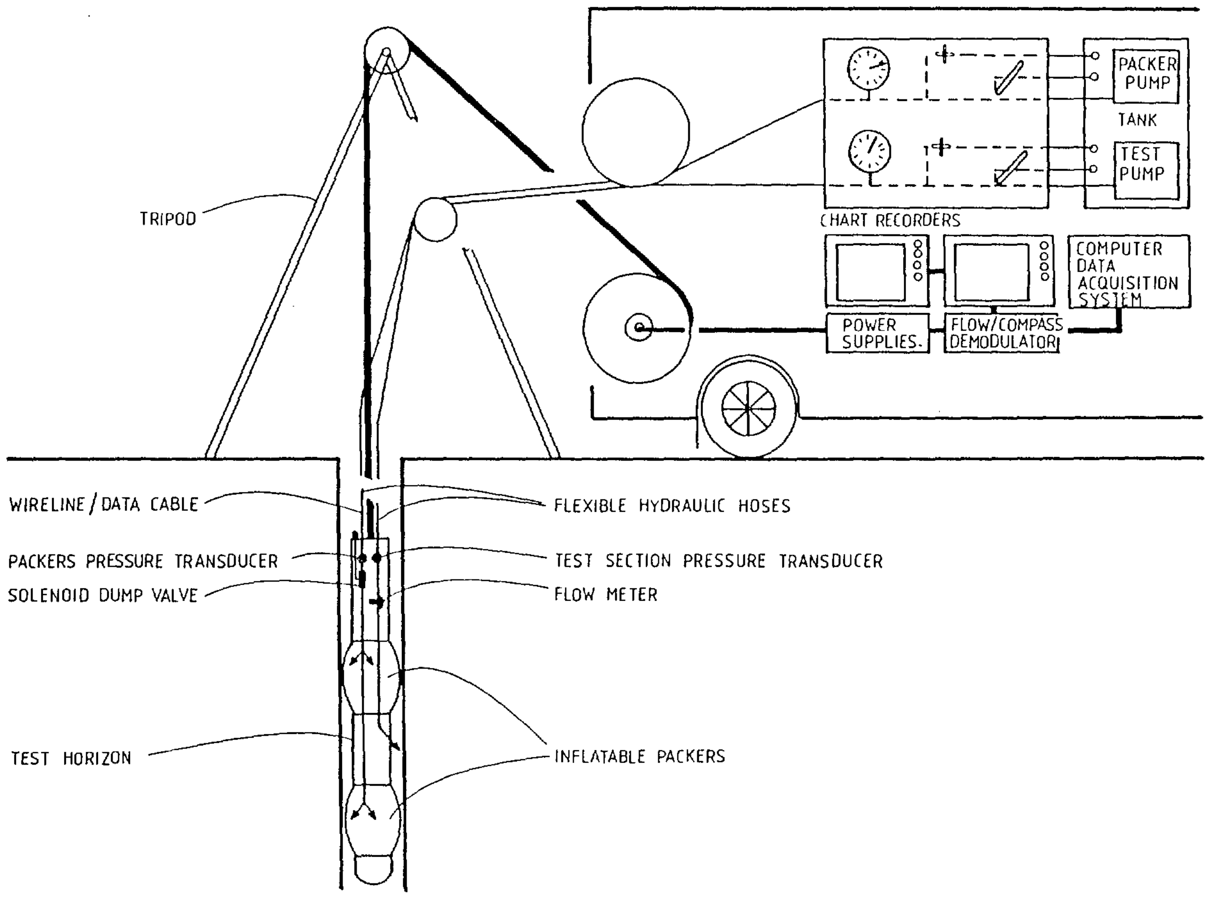


Figure 1

Schematic diagram of the hydrofracture system.

operator of a hydrofracture system to maintain a higher pressure in the packers than in the test section while still expecting crack initiation in the test section. In other words, there is, in each test, a safety margin for the operator and as long as Δp is kept smaller than this margin, crack initiation will proceed in the test section.

In this Record we examine the soundness of this tenet and develop a theory which allows the extent of the operator's safety margin to be evaluated. We then test our model against hydrofracture field data from three boreholes penetrating granitic rocks which have previously been reported by Enever and Chopra (1986) and Chopra and Enever (1987).

2. Theory

A generalised stress state existing in a body of rock can be described in terms of the normal stresses on three mutually orthogonal principal planes across which there is zero shear stress. The normal stresses on each of these principal planes are called the principal stresses, σ_1, σ_2 and σ_3 respectively. By convention the magnitudes of these principal stresses are ranked as $\sigma_1 > \sigma_2 > \sigma_3$ with compressive stresses taken as being positive and tensile stresses as negative.

Since shear stresses cannot exist on a solid-fluid interface, it follows that a plane tangential to the solid surface of the Earth must be a principal plane and its normal directed into the Earth, a principal stress direction. The state of stress in rocks near the surface of the Earth, in areas with gentle topography, can therefore be described in terms of one approximately vertical and two approximately horizontal principal stresses.

The stress state attendant on the hydraulic fracturing of a vertical borehole can thus be modelled in terms of a pressurised circular hole subjected to a biaxial stress field at infinity. The radial and tangential stresses around such a borehole penetrating a homogeneous, isotropic and linearly elastic medium can be expressed as follows:

Radial stress

$$\sigma_r = \frac{1}{2}(\sigma_1+\sigma_2)(1-R^2/r^2) + PR^2/r^2 + \frac{1}{2}(\sigma_1-\sigma_2)(1-4R^2/r^2+3R^4/r^4)\cos 2\theta \qquad (1)$$

Tangential Stress

$$\sigma_\theta = \frac{1}{2}(\sigma_1+\sigma_2)(1+R^2/r^2) - PR^2/r^2 - \frac{1}{2}(\sigma_1-\sigma_2)(1 + 3R^4/r^4)\cos 2\theta \qquad (2)$$

(Jaeger and Cook, 1976; p. 251)

where:

σ_r = radial stress component
σ_θ = tangential stress component
P = the pressure in the borehole
R = the radius of the borehole
r = the radial distance from the centre of the borehole and,
θ = a polar coordinate perpendicular to the borehole axis which is zero in the direction of σ_1.

At the wall of the borehole R = r and equations (1) and (2) become:

$$\sigma_r = P \qquad (3)$$

and

$$\sigma_\theta = \sigma_1 + \sigma_2 - P - 2(\sigma_1 - \sigma_2)\cos 2\theta \qquad (4)$$

It can be seen from (4) that the tangential stress in the borehole wall σ_θ varies between a maximum $\sigma_{\theta(max)} = 3\sigma_1 - \sigma_2 - P$ for $\theta=\pi/2$ and a minimum, $\sigma_{\theta(min)} = 3\sigma_2 - \sigma_1 - P$ for $\theta=0$. The minimum tangential stress in the borehole wall becomes negative (i.e. tensile) when $P > 3\sigma_2 - \sigma_1$.

For such a tensile stress to produce a fracture in impermeable rock in the borehole wall, the limiting strength of the rock must be reached, i.e.

$$P = 3\sigma_2 - \sigma_1 + S \tag{5}$$

where: S = the tensile strength of the rock

In permeable rocks the role of fluid pressure in the pores must also be considered. Since the pressure in these pores is hydrostatic, it follows that there will be a component of pressure in the direction of $\sigma_{\theta(min)}$. This component of pressure will have the effect of facilitating the formation of a crack in the borehole wall perpendicular to $\sigma_{\theta(min)}$. Hence, the fluid pressure (P_i) in the borehole necessary to initiate a crack in the borehole wall is given by:

$$P_i = K^{-1}.(3\sigma_2 - \sigma_1 + S - (2-K)P_o) \tag{6}$$

(Haimson, 1978)

where: P_o = the pore pressure in the rock of the borehole wall and,
K = a poro-elastic parameter with values between 1 and 2.

Haimson (1978) states that the value of K is 1 for the situation where the rock is impermeable to the fluid and 2 when the rock matrix compressibility and the rock bulk compressibility are equal, or when Poisson's ratio equals 0.5. The parameter K can be evaluated from simulated hydrofracture tests carried out on core samples in the laboratory. Such studies have found that K varies with $3\sigma_2 - \sigma_1$ but that it can be taken as being approximately 1 in the range $0 < P_i - P_o - S/K < 25$ MPa and 2.0 for $P_i - P_o - S/K > 50$ MPa (ibid). Although Haimson suggests that K can have values between 1 and 2, Alexander (1983) pointed out that the lower limit of K may in fact be closer to 1.25.

The pressure (P_p) exerted by the packers in a hydrofracture tool that is sufficient to initiate a vertical crack in the borehole wall is given by:

$$P_p = 3\sigma_2 - \sigma_1 + S - P_o \tag{7}$$

Note that in this case, since the pressure is transmitted by a rubber membrane rather than by fluid, there is no poro-elastic effect (i.e. K=1).

Equation (7) may be re-written in the form:

$$P_p = [3\sigma_2 - \sigma_1 + S - (2-K)P_o] - (K-1)P_o$$

or

$$P_p = K.P_i - (K-1)P_o \tag{8}$$

Now if we define the margin of pressure (Ω) in favour of fracture initiation in the test interval as $P_p - P_i$ then we can write from (8):

$$\Omega = (K-1)(P_i - P_o) \tag{9a}$$

Substitution of (6) into (9a) yields:

$$\Omega = [3\sigma_2 - \sigma_1 + S - (2-K)P_o] - \{[3\sigma_2 - \sigma_1 + S - (2-K)P_o]/K\} - (K-1)P_o$$

which simplifies to:

$$\Omega = [(K-1)/K].(3\sigma_2 - \sigma_1 + S - 2P_o + KP_o) - (K-1)P_o$$

and re-arranging gives:

$$\Omega = [(K-1)/K].(3\sigma_2 - \sigma_1 + S - 2P_o + KP_o) - [(K-1)/K].(KP_o)$$

This then leads to the relation:

$$\Omega = [(K-1)/K].(3\sigma_2 - \sigma_1 + S - 2P_o) \tag{9b}$$

which may also be written using (7):

$$\Omega = [(K-1)/K].(P_p - P_o) \qquad (9c)$$

Equations (9) allow the margin of pressure in favour of crack initiation in the test section to be evaluated for a given hydrofracture test provided the poro-elastic constant K for the rock being tested is known and either:

a) the pressure necessary to initiate the crack is known or,
b) the maximum and minimum principal stresses and the rock strength can be estimated (e.g. from a preceding test at an adjoining depth interval).

Provided the pressure differential between the packers and the test section (Δp) is kept smaller than this value of Ω, the induced fracture can be expected to initiate in the test section.

As mentioned after equation (6) above, K can be evaluated by laboratory measurements in simulated hydrofracture tests carried out on core samples from each borehole. Sometimes however, a K value is not available for the rock at a particular site, either because the laboratory tests have not yet been carried out, or because core is not available. It is therefore useful to examine the sensitivity of Ω to variations in K.

Scrutiny of equations (9a,b,c) indicates that as K varies between its theoretical limits of 1 and 2, (K-1)/K varies between 0 and 0.5 and (K-1) varies between 0 and 1. In other words, Ω is quite sensitive to the K value.

Knowledge of the value of K is also necessary if the value of the maximum principal stress is to be correctly calculated from the hydrofracture test data using equation (6). In the absence of laboratory results, σ_1 has often been estimated by assuming, a K value of 1 (e.g. Haimson, 1978; Enever and Chopra, 1986). This practice can obviously introduce errors into the σ_1 estimates however and it is therefore useful to assess their likely magnitude. In this case the sensitivity of the σ_1 estimate to the value of K can be evaluated as follows.

Consider two values of K denoted by K and K'(=1) which result in two estimates of the maximum principal stress from (6), σ_1 and σ'_1 respectively. i.e.

$$\sigma_1 = 3\sigma_2 - KP_i + S - (2-K)P_o$$

and

$$\sigma'_1 = 3\sigma_2 - K'P_i + S - P_o$$

then

$$\Delta\sigma = \sigma'_1 - \sigma_1 = (K-1)(P_i - S - P_o)$$

now since from (6)

$$KP_i - S - KP_o = 3\sigma_2 - \sigma_1 - 2P_o$$

then

$$\Delta\sigma = [(K-1)/K].\{3\sigma_2 - \sigma_1 - 2P_o\}$$

or by dividing both sides by σ_1

$$\Delta\sigma/\sigma_1 = [(K-1)/K].\ \{(3/n) - 1 - 2P_o/\sigma_1\} \qquad (10)$$

where: $n = \sigma_1/\sigma_2$

For measurements made in shallow boreholes, the term $2P_o/\sigma_1$ is negligible. Hence for data from such holes, the fractional error introduced to σ_1 by the assumption K=1 ranges from twice the fractional error in K for n=1, to half that in K for n~2, to negligible values for n~3.

3. Case Studies

The margin of pressure in favour of crack initiation in the test section Ω has been evaluated from hydraulic fracture test data from three sites in Australia where in-situ stress measurements have been made. The results from these sites have been reported previously by Enever and Chopra (1986) and Chopra and Enever (1987).

1) Berrigan, NSW

A summary of the hydraulic fracture data collected at this site is given in Table 1 together with the interpreted values of the maximum and minimum horizontal principal stresses and the location of the initiated crack. Calculations of Ω from these data are of interest because these tests include examples where cracks initiated in the test section as well as an example where the crack initiated under the packers.

Before Ω can be evaluated however, the value of the poro-elastic constant K must be known for the Berrigan granite. This parameter can be estimated in two ways: By laboratory testing of core samples and, by analysis of the hydraulic fracture field results.

The results of a series of laboratory tests with this rock are plotted in Figure 2 (unpublished data of Enever and Chopra, 1986). These data represent the results of 16 simulated hydrofracture experiments on cores of Berrigan granite of 6.3 cm diameter and lengths of approximately 15 cm. The material tested was obtained from depths between 174 and 194 metre. Each core sample was cut to length and its ends were ground and polished prior to the drilling of a central hole of ~5 mm diameter. The samples were then inserted into a biaxial testing frame which permitted the confinement of each sample under a uniform radial compressive stress. Once an appropriate confining pressure had been applied to the sample in each test, an increasing fluid pressure was applied to the central bore until tensile failure of the sample occurred.

The value of K can be calculated from the data of Figure 2 by using equation (6) and recalling that for the laboratory tests, the

Table 1

Berrigan Field Data*

Depth (metre)	Pore Press- -ure (MPa)	Pressure at Crack Initiation. In Test Section (MPa)	In Packers (MPa)	Reopening Pressures (MPa)	σ_2 (MPa)	σ_1 (MPa)	Fracture Location
4-5	0	11.6	14.2	5.7- 6.0	5.6- 6.0	11.1- 12.0	packer
69-70	0.7	15.5	16.2	5.5- 5.6	5.3- 5.6	9.7- 10.5	test section
100-101	1.0	17.4	18.9	5.6- 6.3	4.9- 6.0	8.1- 10.7	test section
125-126	1.3	18.5	19.7	6.7	6.1- 6.3	10.3- 10.9	test section
154-155	1.5	20.7	21.5	7.0	5.7- 6.3	8.6- 10.4	test section
168-169	1.7	18.6	19.0	8.4	7.7- 8.0	13.0- 13.9	test section

* data of Enever and Chopra (1986)

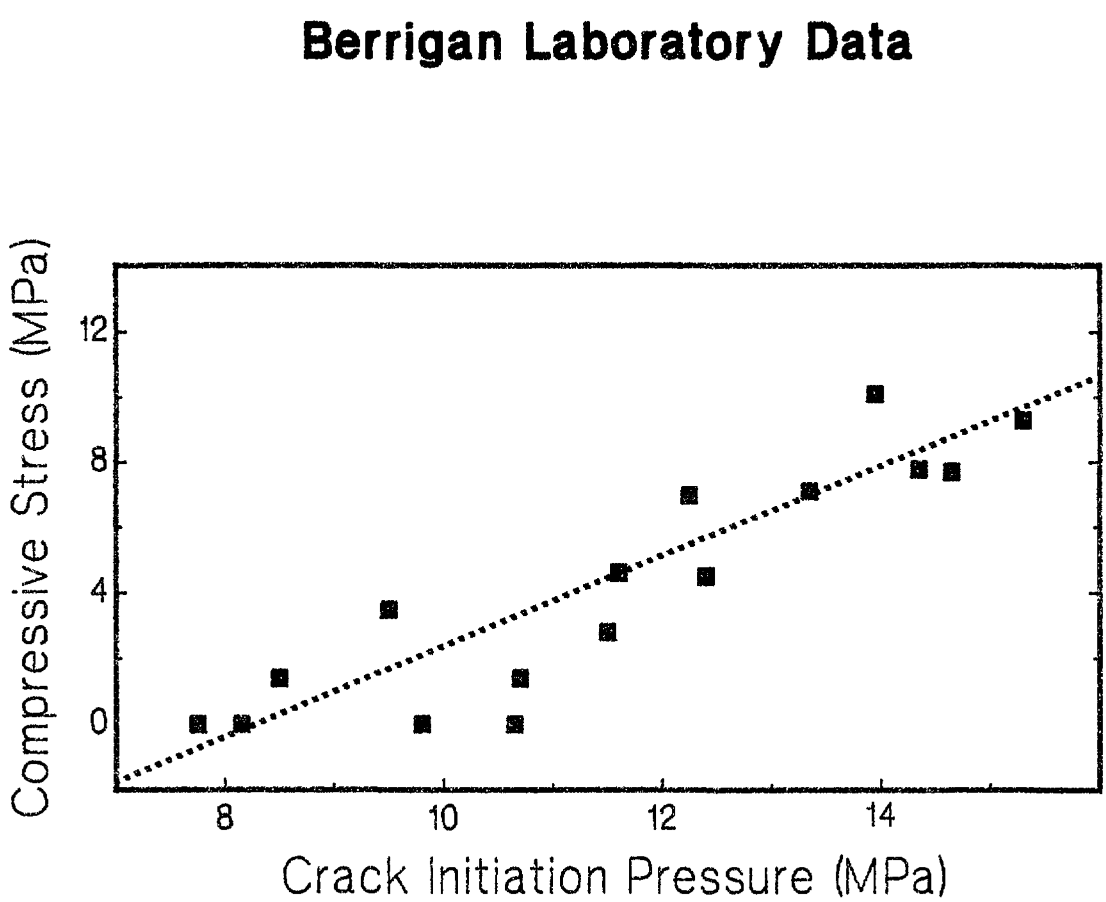


Figure 2

Results of laboratory tests with core samples of Berrigan granite. The result of the linear regression of the compressive stress (σ_c) data against the crack initiation pressures (P_i) is also shown (see text).

ambient pore pressure in the samples is zero and $\sigma_1 = \sigma_2 = \sigma_r$ where σ_r = the applied radial compressive stress i.e.

$$P_i = K^{-1}(\sigma_c + S_{lab}) \qquad (11a)$$

where:

$\sigma_c = 2\sigma_r$

S_{lab} = the laboratory determined strength of the rock

or:

$$\sigma_c = K.P_i - S_{lab} \qquad (11b)$$

thus the slope of the linear trend defined by the data in Figure 2 is equal to K and the intercept is equal to S_{lab}. A linear regression analysis of the data in Figure 2, with all the error assumed in the σ_c values, has been performed. Assignment of all error to the σ_c values is appropriate because, unlike P_i, σ_c is not directly measured (rather it is calculated on the basis of an assumed failure criterion {i.e. equation (6)} with the further assumption that the crack initiates precisely at the bore-wall of the sample). This statistical procedure has the added advantage that the intercept estimate obtained is a function of S_{lab} only and not of K (cf. equations 11b and 11a).

The linear regression yields estimates of 1.36 ±0.36 for the slope and -11.44 MPa for the intercept (with the error quoted as ±2 standard deviations, i.e. 95% confidence limits). These estimates correspond to K and $-S_{lab}$ respectively. The correlation coefficient, r^2 for this fit is 0.8059 which indicates that 80.59% of the variation in the data can be explained in terms of the regression.

The value of K obtained from the regression can be tested against the field result obtained at 4-5 metre depth. Since in this experiment, the fracture initiated under a packer, the value of P_i is constrained to lie between the maximum pressure attained in the test section ($P_{max.t.s.}$) and the peak pressure in the packers ($P_{max.seals}$).

i.e. $P_{max.t.s.} < P_i < P_{max.seals}$

Substitution of this result in (8) with $P_p = P_{max.seals}$ yields:

$$K < (P_{max.seals} - P_o)/(P_{max.t.s.} - P_o) \tag{12}$$

Substitution of the data of Table 1 with P_o=0.04 MPa into (12) then gives the result K < 1.23. Although this limiting value for K lies within the error envelope obtained from the regression of the laboratory data, it differs somewhat from the mean estimate of 1.36. This departure may reflect differences between the rock at 4-5 metre depth and that in the depth interval of 174-194 metre from which the laboratory samples were obtained. Such differences could derive from the greater influences of weathering in near-surface rocks.

In view of the lack of laboratory results on samples from the near-surface, the 4-5 metre test data have been analysed using the estimate of K obtained from the field test. The analyses of the data from the other Berrigan tests have been made using the mean laboratory determined K estimate.

These estimates of K can be used in the calculation of Ω for the 5 Berrigan hydrofracture tests with equations (9a) and (9c). The results of these calculations are given in Table 2 together with field estimates of the rock strength calculated from the field data. The latter calculations have been made by solving (6) using the data for the crack initiation and the subsequent crack re-openings:

i.e. $P_i = K^{-1}(3\sigma_2 - \sigma_1 + S - (2-K)P_o)$

and $P_r = K^{-1}(3\sigma_2 - \sigma_1 - (2-K)P_o)$

which lead to:

$$S_{field} = K(P_i - P_r) \tag{13}$$

Table 2

Berrigan Results

Depth (metre)	Ω^{x} (MPa)	S_{field} (MPa)	S_{lab} (MPa)	Fracture Location
4-5	2.65^{+}	11.4^{*}	-	packer
69-70	5.32	13.5	-	test section
100-101	5.90	15.6	-	test section
125-126	6.19	16.0	-	test section
154-155	6.91	18.6	-	test section
168-169	6.08	13.9	-	test section
174-194	-	-	11.4	-

^{x} calculated using equation (9a) with K=1.36 unless otherwise indicated

$^{+}$ calculation of Ω in this case was made using (9c) with K=1.23 (see text)

* calculation of S_{field} has been made in this case with P_p in place of P_i in equation (13) because the crack initiated under the packer. The calculation is only approximate because P_r in this test may have been compromised by the packer (see discussion by Enever and Chopra; 1986).

The data of Table 2 are interesting in that the test at 4 m depth which produced a crack under a sealing packer, is distinguished from the other 5 tests by a significantly lower Ω value. The other apparent difference between this test and the results from deeper levels in the hole, viz. the lower value of S_{field}, may be the result of increased weathering near the surface or it may be due to errors in the analysis of the 4 metre depth data (see Table 2).

2) Lancefield, Vic.

The hydraulic fracture data obtained from a single test in a shallow borehole at Lancefield are given in Table 3. Also tabulated are the interpreted values of the maximum and the minimum horizontal principal stress at the site. As reported by Enever and Chopra (1986), this test resulted in the formation of a vertical fracture under one of the packers. The pressure recorded in the test section at the time of crack initiation was therefore less than that required to produce a crack (i.e. $P_{test\ section} < P_i$).

Calculation of Ω from these field results is complicated by a lack of laboratory data suitable to directly estimate the magnitude of K. The laboratory data that are to hand are plotted in Figure 3, after Enever and Chopra (1986). These results suggest that the crack initiation pressure for the Lancefield granodiorite is essentially independent of the rate of pressurisation of the samples. The mean crack initiation pressure estimated from these measurements is 11.1 ± 1.4 MPa (with the error quoted as ± 1 standard deviation). This value corresponds to S_{lab}/K from (11a) since $\sigma_r = 0$ in these tests.

An estimate of the <u>in-situ</u> rock strength (S_{field}) can be obtained using (7) since the crack in the Lancefield test initiated under the packers. The result of this calculation, using the data given in Table 3, is $S_{field} = 11.0$ MPa.

Now since the laboratory tests with the Lancefield granodiorite were made on core samples from the same depth interval in the hole as that used in the hydrofracture test, S_{field} should be equivalent to S_{lab}. This assumption will hold provided that the laboratory tests were effective hydrofracture simulations. Thus from $S_{lab}/K = 11.1 \pm 1.4$ MPa we obtain $0.98 < K < 1.06$, or after considering the theoretical aspects, $1.00 < K < 1.06$.

This limited range of K estimates can be used to calculate a range of Ω values using (9c). These calculations result in $0 < \Omega < 0.12$ MPa. Thus the estimates of Ω are again small for the case where the crack initiated under the packer rather than in the test section.

Table 3

Lancefield and Wongan Hills Field Data*

Depth (metre)	Pore Press--ure (MPa)	Pressure at Crack Initiation. In Test Section (MPa)	In Packers (MPa)	Reopening Pressures (MPa)	σ_2 (MPa)	σ_1 (MPa)	Fracture Location
Lancefield							
10	0	10.9	11.6	4.2-4.6	3.9	10.1-12.1	packer
Wongan Hills							
66-67	0.7	9.5	9.6	3.9-4.2	4.3	16.8[x]	packer
69-70	0.7	11.4	11.5	3.9-4.2	6.6	21.8[x]	packer

* data of Enever and Chopra (1986)

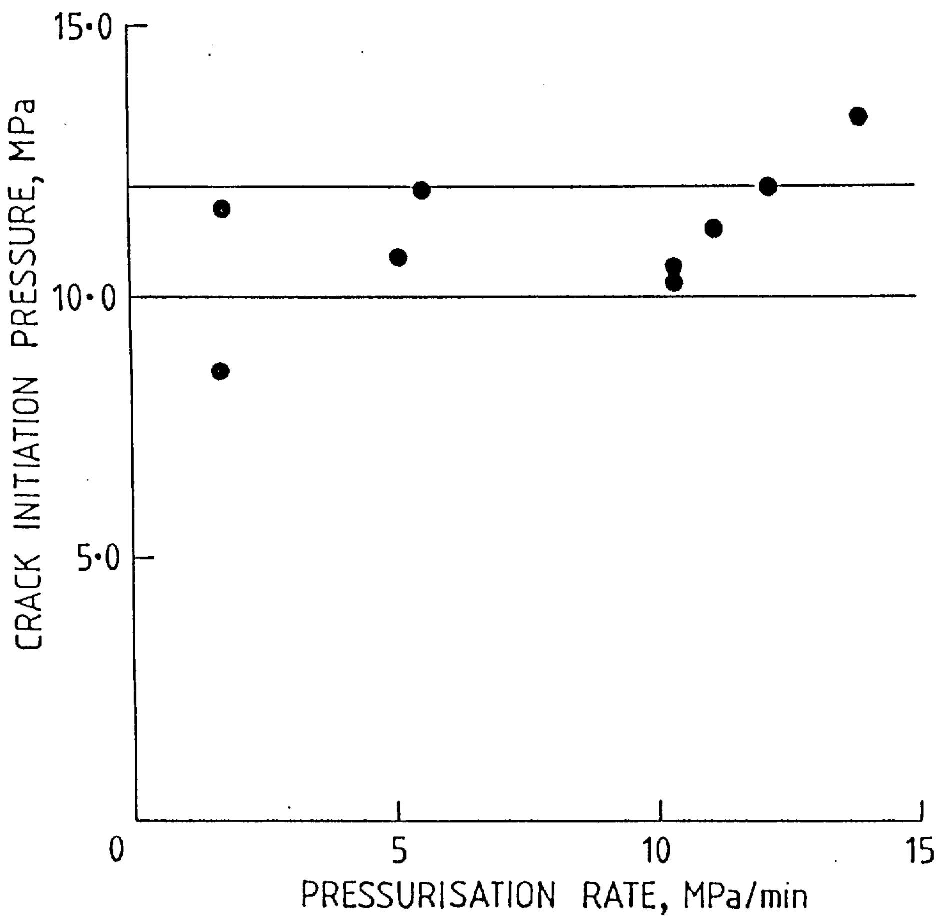


Figure 3

Results of laboratory tests with core samples of Lancefield granodiorite.

3) Wongan Hills, WA

The hydraulic fracture test data obtained in two tests at Wongan Hills by Denham et al (1987) are listed in Table 3. Estimates of σ_2 and calculated values of σ_1 that have been obtained from these data are also given. As remarked earlier by Enever and Chopra (1986), both the tests conducted at Wongan Hills resulted in the initiation of fractures under the sealing packers.

The results of laboratory tests made on core samples from the Wongan Hills borehole by Enever and Chopra (1986) are plotted in Figure 4. The radial tensile stress data plotted in the figure have been linearly regressed against the crack initiation pressures. The slope of the resulting fit is -0.653 ±0.267 (with the error quoted as ~2 standard deviations, i.e. 95% confidence limits), the intercept is 9.93 MPa, and the correlation coefficient $r^2 = 0.6848$. The latter estimate indicates that the degree of scatter about the fit is relatively large. Estimates of K and S_{lab} made from the slope and intercept values of the fit are $1.53^{+0.47}_{-0.44}$ and 15.2 MPa respectively. This estimate of K is of little value since the range quoted ($1.08 < K < 2.00$) spans virtually the full scope of permissible K values. Fortunately, two additional independent estimates of K can be obtained from the field data by applying similar analyses to that used with the Berrigan 4-5 metre depth data above. Both the Wongan Hills tests provide good opportunities to estimate K in this way, since Δp was in each case small. Use of (8) with the data from the two tests yields the same result, viz, $K < 1.01$. Thus we have, after considering the theoretical limits on K, the result $1.0 < K < 1.01$.

Values of Ω have been calculated for the two Wongan Hills tests using equation (9c) with the estimated range of K given above and the relevant σ data in Table 3. The results of these calculations give $0 < \Omega < 0.09$ MPa and $0 < \Omega < 0.11$ MPa for the 66-67 and 69-70 metre depth tests respectively.

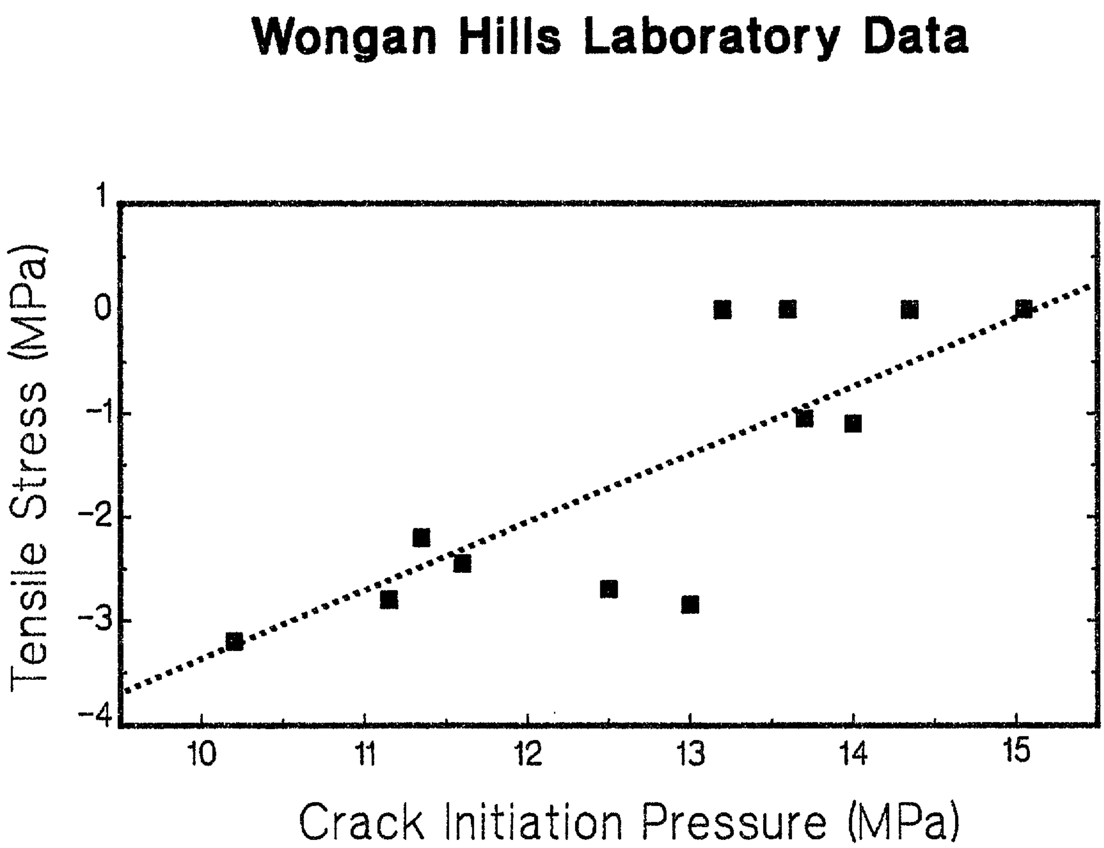


Figure 4

Results of laboratory tests with core samples of Wongan Hills meta-granodiorite. The result of the linear regression of the tensile stress data against the crack initiation pressures is also shown (see text).

.A.J.

4. Discussion

The results of the calculations of Ω for the three field sites are summarised in Table 4. Also included in Table 4 are the values of $\Omega-\Delta p$ and $3\sigma_2 - \sigma_1$ calculated from the data of each test as listed in Tables 1 and 3.

Table 4

Summary of Results

Test Site	Test Depth (metre)	Ω (MPa)	$\Omega - \Delta p$ (MPa)	$3\sigma_2 - \sigma_1$ (MPa)	Fracture Location
Berrigan	4-5	0 to 2.65	-2.6 to 0.45	4.8-6.9	packer
Berrigan	69-70	5.32	4.62	5.4-7.1	test section
Berrigan	100-101	5.90	4.40	4.0-9.9	test section
Berrigan	125-126	6.19	4.99	7.4-8.6	test section
Berrigan	154-155	6.91	6.11	6.7-10.3	test section
Berrigan	168-169	6.08	5.68	9.2-11.0	test section
Lancefield	10-11	0 to 0.12	-.7 to -.58	1.6 to -.4	packer
Wongan Hills	66-67	0 to 0.09	-.1 to -.01	-4.8 to -3.0	packer
Wongan Hills	69-70	0 to 0.11	-.1 to +.01	-2.9 to -1.1	packer

The estimates of the failure criterion $\Omega - \Delta p$ that are listed in Table 4 have been plotted in Figure 5 against the location of fracture initiation. As can be seen in this figure, the data are clearly segregated into two fields. As predicted by the theory, those tests in which the fracture initiated under the packers have values of $\Omega - \Delta p < 0$ MPa. On the other hand, the tests at Berrigan which produced fractures in the test section are all characterised by $\Omega - \Delta p > 0$ MPa. Thus the criterion developed here would appear to be able to readily discern between the two types of test results with the present data.

Analysis of Possible Errors in Ω - Δp

While the Ω - Δp criterion has been found to discriminate adequately between the two types of results for the 9 tests reported here, its successful application to new data in the future will depend upon an understanding of the potential sources of error in its calculation. Such sources of error can be broadly divided into two groups: potential errors inherent in the application of the theory and, errors in the data used to calculate the criterion. We will consider these two possible contributions of error in turn.

1) Possible errors in the application of the theory

At the outset it should be emphasised that significant errors in the formulation of the theory and in its application to the test data from Berrigan, Lancefield and Wongan Hills are militated against by the excellent agreement between the stress estimates obtained from the hydrofracture and overcoring methods at the 3 sites (Enever and Chopra, 1986). Nevertheless, the possibility of errors of this type occurring when the theory is applied to data from other sites in the future cannot be completely dismissed. Factors which might possibly contribute errors could include:

i) Membrane effects at the packer/wall-rock interface.
Such effects might perhaps lead to some concentration of tangential stress in part of the borehole wall thereby

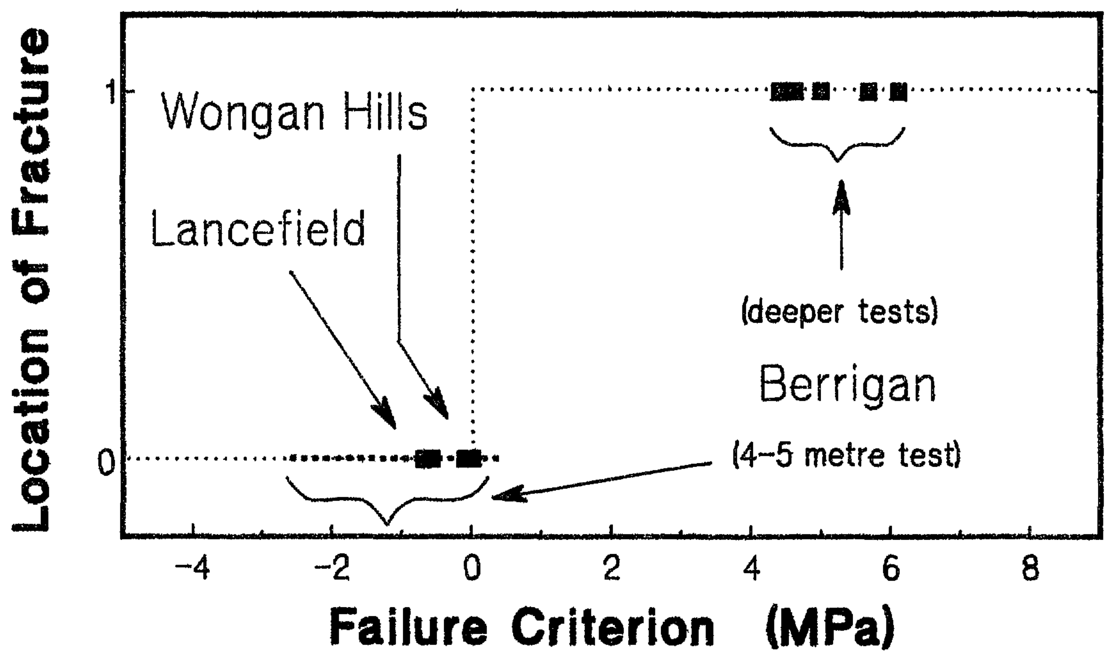


Figure 5

Plot of the failure criterion $\Omega - \Delta p$ against the locus of fracture initiation for nine hydraulic fracture tests.

Location of fracture: 1 = crack initiated in test section
0 = crack initiated under one or other of the packers.

Light dotted line = the theoretical model

Heavy dotted line = the range of $\Omega - \Delta p$ for the Berrigan 4-5 metre test with $1.0 < K < 1.23$ (see text).

increasing the tendency for crack formation under the packers beyond that suggested by (7). Such a concentration of stress might occur for example at the root of a corrugation or other irregularity in the borehole wall.

ii) Pore pressure build-up behind the packers during testing. The theory assumes the absence of fluid at the interface of the packer and the rock of the borehole wall. In practice some residual water is likely to be trapped there during the initial inflation of the packers and more might conceivably work its way into this region from the pressurised test section via interconnected surface pores and micro-cracks. The presence of such fluid would again have the effect of increasing the propensity for crack initiation by the packers beyond that suggested by (7).

2) Possible errors in the data used in the analyses.

The value of Ω is generally calculated using either (9a) or (9c) depending on whether the hydraulic fracture initiated in the test section or under the packers. Reference to these equations indicates that Ω is a function of three experimentally determined quantities (P_o and K together with either P_p or P_i). Thus it is only through these data and Δp that experimental errors can be introduced to Ω - Δp. We will consider the potential sources of error in each of these quantities separately.

i) Possible errors in the estimation of P_o.

The analyses of all the hydrofracture data presented here have been made with the assumption that the standing water level in the boreholes was in each case at the surface. This assumption has been made in the absence of specific data regarding the true water level and is clearly a source of error.

The data from the Lancefield test are likely to be relatively little affected because of the shallowness of the hole (10 metre). The maximum error in P_o in this case is -0.1 MPa which would result in a deviation from the value of Ω in

Table 4 of only +1%.

The errors introduced to the Berrigan and Wongan Hills data cannot be accurately assessed without knowledge of the true standing water levels existing in each hole at the time of testing. Maximum error contributions can again be calculated however by assuming that the water level is no higher in the hole than the depth of each individual test. These calculations suggest maximum deviations from the Ω values in Table 4 of +0.3% to +10% for the Berrigan tests and +6% for the Wongan Hills tests.

ii) Possible errors in the estimation of P_p.

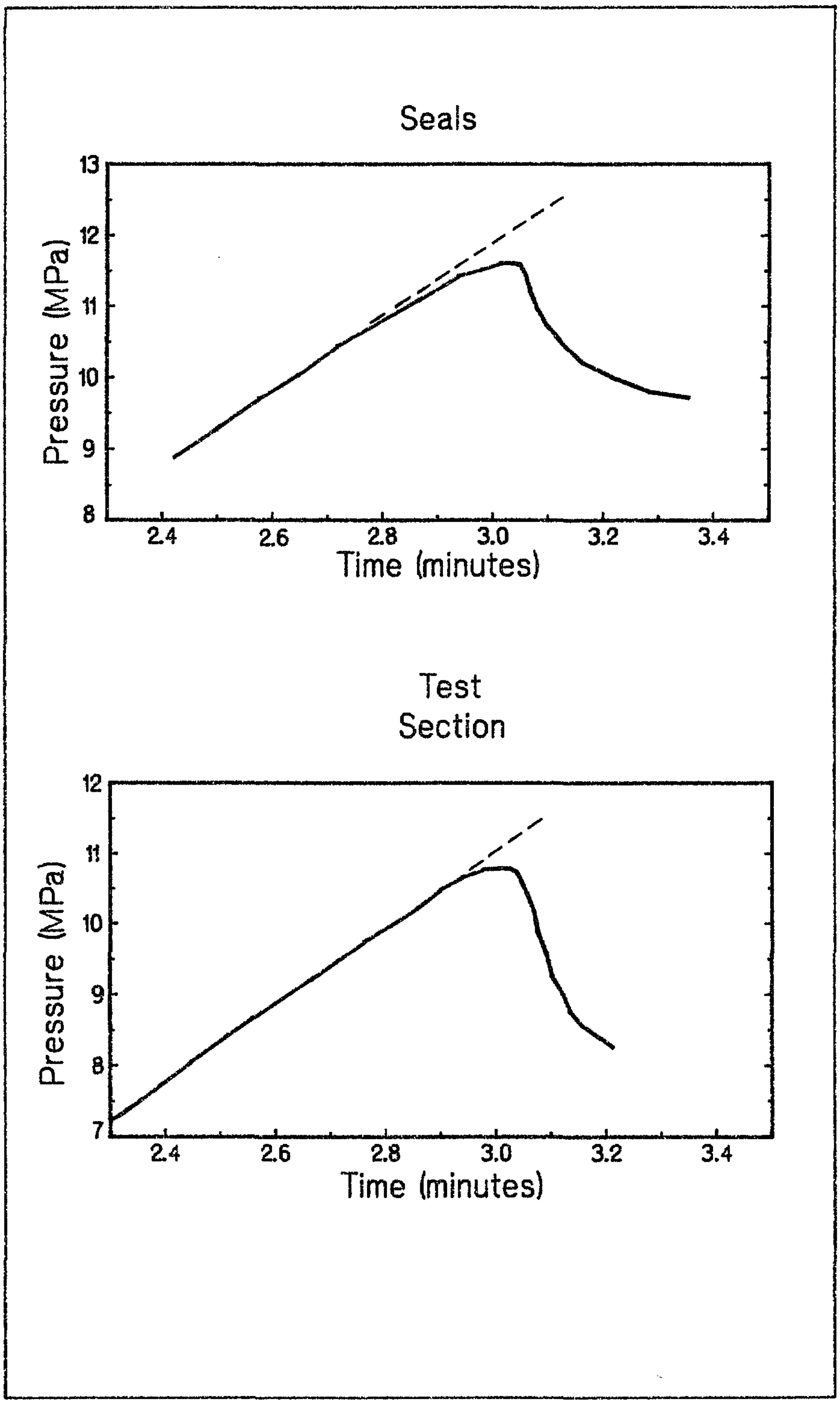
In those tests in which the fracture initiated under one or other of the sealing packers, the maximum pressure attained in the packers has been taken as being equal to P_p, in line with common practice (see for example, Table 2 of Enever and Chopra, 1986).

To examine the validity of this procedure, the pressure-time data for the Lancefield test just prior to, and immediately after, crack initiation are plotted in Figure 6a. For comparison purposes, the equivalent data from the Berrigan test at 155 metre are plotted in Figure 6b. As discussed by Enever and Chopra (1986), and amply illustrated in these figures, crack initiation under the packers leads to a more rounded pressure-time curve than is characterised for cracking initiated in the test section.

The early departure from a linear pressure increase with time that is seen in the seals data from the Lancefield test probably marks the true initiation of cracking, given the lack of any such precursor in the Berrigan data. Thus the estimate of P_p used for the Lancefield data of 11.6 MPa is probably too large by ~0.9 MPa. Similar errors could be expected in the P_p estimates from the other tests in which cracking initiated under the sealing packers.

The broadness of the failure peak in pressure-time space is consistent with a rapid fall-off in σ_θ with distance from the

Data from Lancefield Test at 10 metre



<u>Figure 6a</u>

Abridged pressure-time data from the Lancefield test illustrating the typical features associated with crack initiation under one or other of the packers. The dashed lines represent the continuation of the linear trends followed at early times.

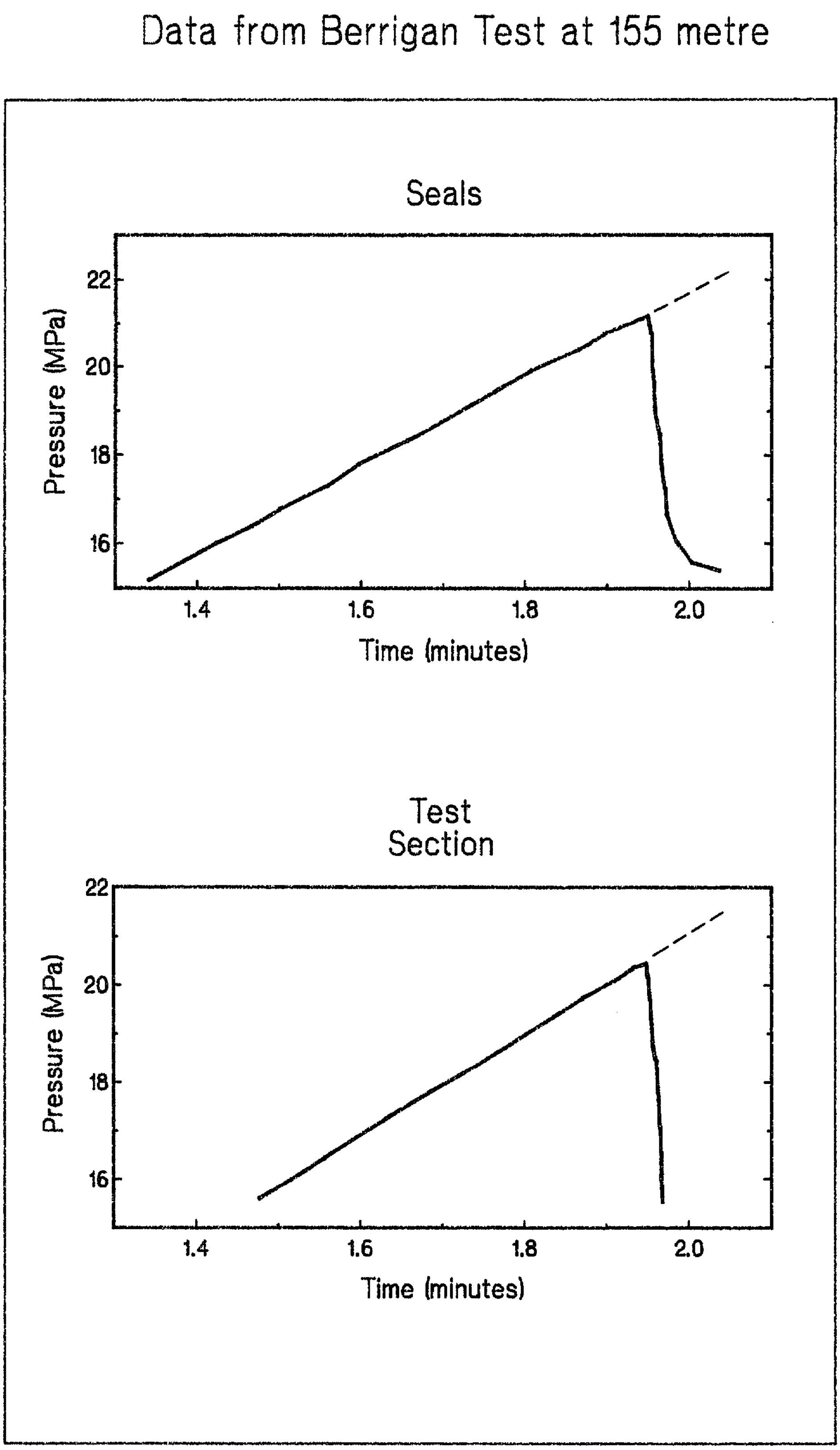


Figure 6b

Abridged pressure-time data from the Berrigan test at 155 metre illustrating the typical features associated with crack initiation in the test section. The dashed lines represent the continuation of the linear trends.

borehole axis, as predicted by (2). This situation would be expected to encourage propagation of the initiated fracture along the axis of the borehole with further pressurisation of the packers rather than crack extension out from the borehole. This in turn would make it very likely that fluid from the test section would eventually gain access to the fracture.

iii) Possible errors in the estimation of P_i.
Figure 6b is a typical pressure-time record for a hydraulic fracture test in which crack initiation occurred in the test section. As can be seen in this figure, the rate of pressure increase with time, for both the test section and the sealing packers, is constant prior to the sudden decompression which characterises fracture initiation. This behaviour allows an unambiguous determination of P_i which ensures that the error in this parameter will be small.

iv) Possible errors in the estimation of K
One of the significant findings in the Berrigan and Wongan Hills case studies has been the relatively poor quality of the estimates of K obtained from the laboratory tests. Indeed, the Wongan Hills laboratory results have been found to be practically useless since the 95% confidence limits on the K estimate obtained (viz. $1.08 \leq K < 2.0$) include virtually the entire range of permissible K values.
The approach that has been used here to obtain estimates of K from the field data appears to have been successful in so far as the Ω estimates that have been produced are consistent with the theory's predictions. This approach does not however allow a rigorous assessment of the likely error in the K estimate to be made, which is a matter of concern.
Clearly an improvement of this situation would require an improved method of laboratory testing from which more tightly constrained estimates of K could be obtained. Such estimates should then always be tested against any independent field estimates that might be available.

v) Possible errors in the estimation of Δp.

This item is included in the discussion for the sake of completeness, but is in fact of little importance in the overall error budget for $\Omega - \Delta p$ since it is directly read from the pressure-time record for a given test. Its total error therefore comprises twice the error in the pressure detection circuitry plus any operator reading error.

Potential Errors in σ_1 Arising from the Assumption K=1

It has been customary in the analysis of hydraulic fracture test data to assume that the poro-elastic constant K is approximately 1 (e.g. Haimson, 1978; Enever and Chopra, 1986). As discussed in the Theory section above, the errors introduced by this arbitrary assumption can be evaluated using (10) and the data from a given hydraulic fracture test.

Calculations using this relation have been made for the 9 tests conducted at Berrigan, Lancefield and Wongan Hills and the results are plotted in Figure 7.

These results support the notion that the percentage error in the σ_1 estimate will be greatest when $\sigma_1/\sigma_2=1$ (i.e. for hydrostatic conditions) and increasingly less important for more diverse stress fields. The corollary to this conclusion is that accurate estimation of the value of K, either from the analysis of laboratory or field results, will be crucial when the deviatoric stress levels to be measured are small. The opposite is also true in that when the stress field is substantially non-hydrostatic, exhaustive laboratory testing aimed at the determination of K may be unnecessary.

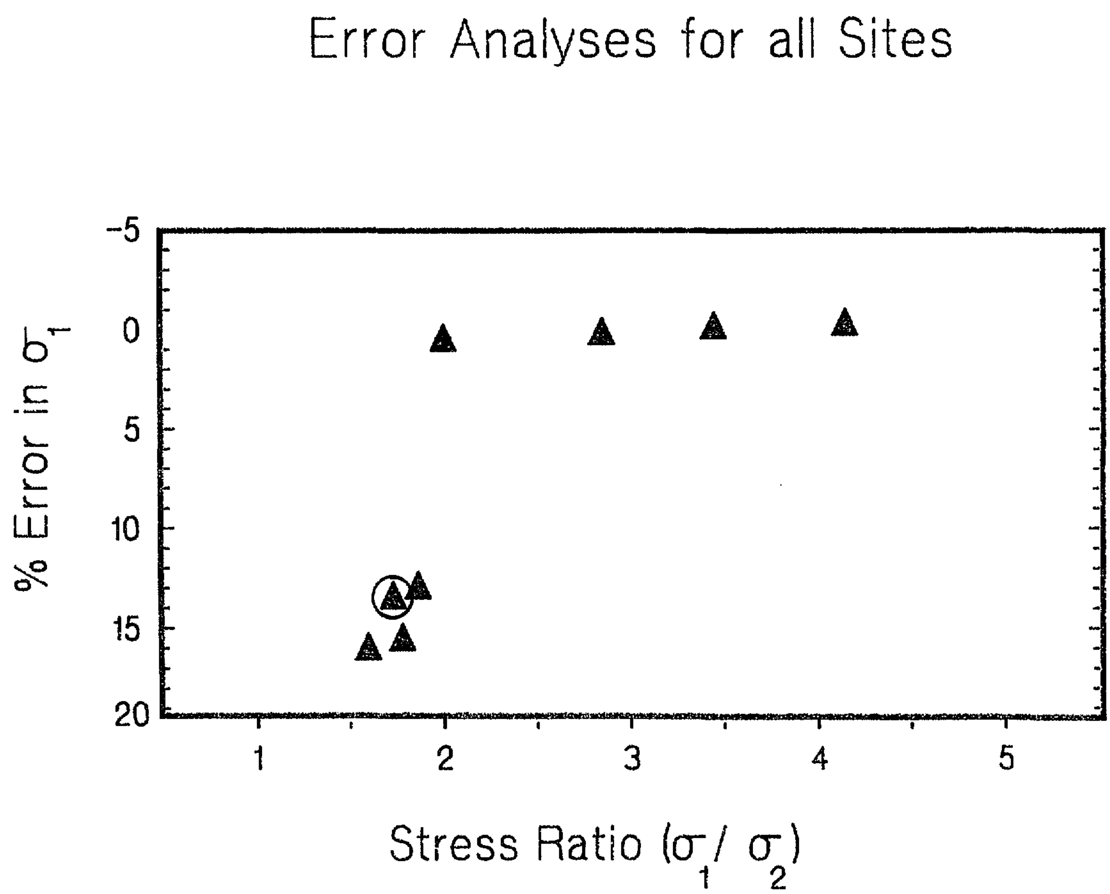


Figure 7

A plot of the percentage error that would be introduced to the σ_1 estimates at the 9 sites by the assumption K=1 (see text).

Comparison with the Alternative Criterion of Enever & Chopra

Enever and Chopra (1986) suggested that the relative magnitudes of σ_1 and σ_2 might themselves directly influence the location of fracture initiation relative to the fracturing tool (i.e. under the packers versus in the test section). They pointed out that for stress states where $\sigma_1 > 3\sigma_2$, σ_θ becomes tensile in parts of the borehole wall without the application of pressure to the borehole. This they speculated might lead to a somewhat different failure criterion during hydrofracture testing. Such a failure criterion, they argued, might be less influenced by fluid penetration of the wall-rocks.

To examine the hypothesis that the magnitude of $3\sigma_2 - \sigma_1$ might influence the locus of fracture initiation, the results for the Berrigan, Lancefield and Wongan Hills tests have been plotted in Figure 8. On first appearance this plot would appear to provide a good basis for separating the tests in which cracks occurred under the packers from those in which the crack initiated in the test section. On closer inspection however it can be seen that the data fall into three fields in terms of $3\sigma_2 - \sigma_1$, with the Berrigan data clustered above 5 MPa since σ_1/σ_2 is relatively small. Similarly, the Wongan Hills data, with their large stress ratio, plot at negative values of $3\sigma_2 - \sigma_1$ and the Lancefield result, where σ_1 is approximately three times the magnitude of σ_2, plots near $3\sigma_2 - \sigma_1 = 0$.

This clustering of the data, when combined with the observation that all the tests at Wongan Hills and Lancefield resulted in initiated cracks of the one type (i.e. under the packers), tends to diminish the credibility of the plot. The demarcation in $3\sigma_2 - \sigma_1$ between those tests in which cracks initiated in the test section (i.e. the 5 deeper Berrigan tests) and those where the cracks formed under the packers (i.e. all other tests) can be seen to be defined almost entirely by the Berrigan 4-5 metre result. Considerably more data from other sites would be needed to support the model before the $3\sigma_2 - \sigma_1$ criterion could be reliably assessed.

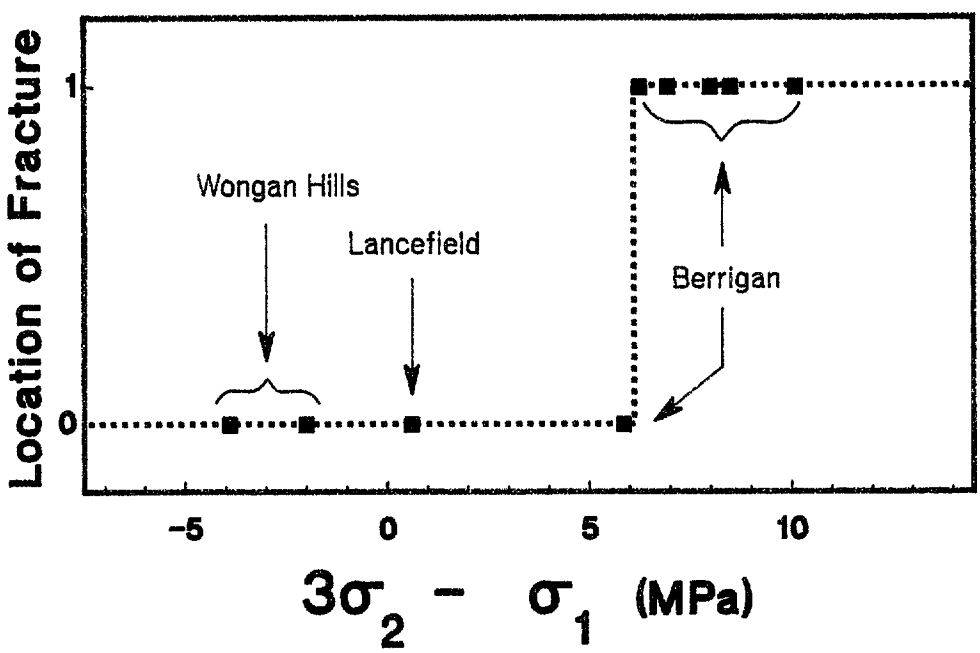


Figure 8

Plot of the criterion $3\sigma_2 - \sigma_1$ against the locus of fracture initiation for nine hydraulic fracture tests.

Location of fracture: 1 = crack initiated in test section

0 = crack initiated under one or other of the packers.

The plot of the criterion $\Omega-\Delta p$ in Figure 5 is less affected by the peculiarities of the available data. The demarcation between the two types of test results is defined in this case by data from different sites with different rock types and widely differing in-situ stress fields. It is also significant that the position of this demarcation at $\Omega - \Delta p = 0$ is theoretically based while that displayed in Figure 8 is, at least at this stage, purely empirical.

Thus although additional data is clearly still needed to further test and better define the application of the $\Omega-\Delta p$ criterion, it would appear to be more soundly based than the $3\sigma_2-\sigma_1$ alternative.

5. Conclusions

A criterion for assessing the location of the crack initiated in hydraulic fracturing experiments conducted in boreholes has been developed. This criterion (Ω) can be evaluated from the pressure-time records of a hydraulic fracture test. Alternatively, Ω may be estimated prior to testing if the approximate magnitude of the in-situ stress field is known and laboratory or field petrophysical data on the rock under test are available. Such prior knowledge of Ω allows an upper limit on the pressure differential existing between the packers and the test section of the hydraulic fracture tool to be calculated. Provided this pressure differential (Δp) is not exceeded, crack initiation can be expected to occur in the test section, which simplifies the analysis of the hydraulic fracture data.

The results from 9 hydrofracture tests made at 3 sites in Australia previously reported by Enever and Chopra (1986) and Chopra and Enever (1987) have been used to test the veracity of the criterion. It has been found that, as predicted by the theory, cracks initiate in the test section when $\Omega - \Delta p > 0$ MPa and under the packers for $\Omega - \Delta p < 0$ MPa.

The possible sources of error in the calculation of $\Omega - \Delta p$ have been analysed. It is suggested that the only significant contributions stem from a probable systematic over-estimation of P_p of the order of 1 MPa in tests in which cracks initiated under one or other of the packers and, from uncertainty in the estimate of the poro-elastic constant K. Limitations in the quality of the data obtained from laboratory tests on some core samples, which have been carried out to determine K, have been highlighted. It is suggested that improved laboratory testing procedures may be needed in order to obtain reliable estimates of K.

6. Acknowledgements

We thank J.R. Enever for permission to use the unpublished laboratory results of Enever and Chopra (1986) on the Berrigan granite.

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