BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD

BMR Record 1987/12

In-situ Stress Measurements With the Hydraulic Fracture Technique

P.N. Chopra and J.R. Enever

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[+] CSIRO Division of Geomechanics
Kinnoul Grove
Syndal Vic 3149

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Abstract

A new hydraulic fracture system has been developed and constructed for use in the measurement of _in-situ_ crustal stress. This system incorporates a down-hole flow meter, a new development which allows much more precise resolution of crack re-opening pressures and greatly aids in the interpretation of the hydraulic fracture pressure records. Hydraulic fracture stress measurements have been made in granitoids at 3 sites in Australia at which independent measurements of the _in-situ_ crustal stress had already been obtained with the overcoring method. In all cases, the results of the hydraulic fracturing and overcoring methods are consistent. This suggests that both methods can reliably determine the stress in the Earth's crust. In the hydraulic fracture tests reported here, two types of induced fracture geometries have been observed: fractures in the test section and fractures under the sealing packers. Each fracture geometry results in a distinctive pressure record. With fractures of the first type, it is shown that use of crack re-opening pressure in the analysis provides reliable estimates of the _in-situ_ stress. With fractures under the packers on the other hand, it has been found that analysis of the results based on crack initiation pressure and the mean laboratory-determined rock strength results in reliable _in-situ_ stress estimates.

1. Introduction

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Mineral Resources, Geology and Geophysics (BMR) have been cooperating for a number of years in a program of regional stress measurements in granite outcrops throughout Australia (Denham et al, 1979; Denham et al, 1980; Denham and Alexander, 1981). The aim of this work has been to investigate the magnitude, orientation and distribution of tectonic stress within the continent, to study the relationship between this stress field and large scale geological structure and, to obtain data for the assessment of earthquake risk.

Initial efforts involved a number of overcoring techniques including the use of United States Bureau of Mines (USBM) borehole deformation gauges and the CSIRO triaxial borehole deformation gauge. These overcoring measurements were made in granite outcrops in close proximity to the surface (generally less than 5 metres depth) at a number of locations throughout Australia (loc. cit.). Where the results obtained are considered to be reliable, they have generally indicated a NE-SW or E-W orientation of the maximum horizontal principal stress.

These results, while they have served to delineate some broad features in the stress field, have also pointed to three serious limitations inherent in the overcoring technique in its application to Australian conditions.

1) The need to carry out overcoring at relatively shallow depths (i.e. less than a few tens of metres) is an important limitation in an Australian context because of the deep weathering profiles that characterise the near surface rocks throughout much of the continent. Such deep weathering can compromise the relevance of near surface measurements because of the possibility of decoupling of the near surface rocks from the underlying crust both through the greater deformability of the weathered material and as a result of the presence of associated open cracks and joints.

2) Near surface stress measurements are also likely to include

stresses associated with diurnal and seasonal temperature changes that can be as great as 50 ^{o}C.

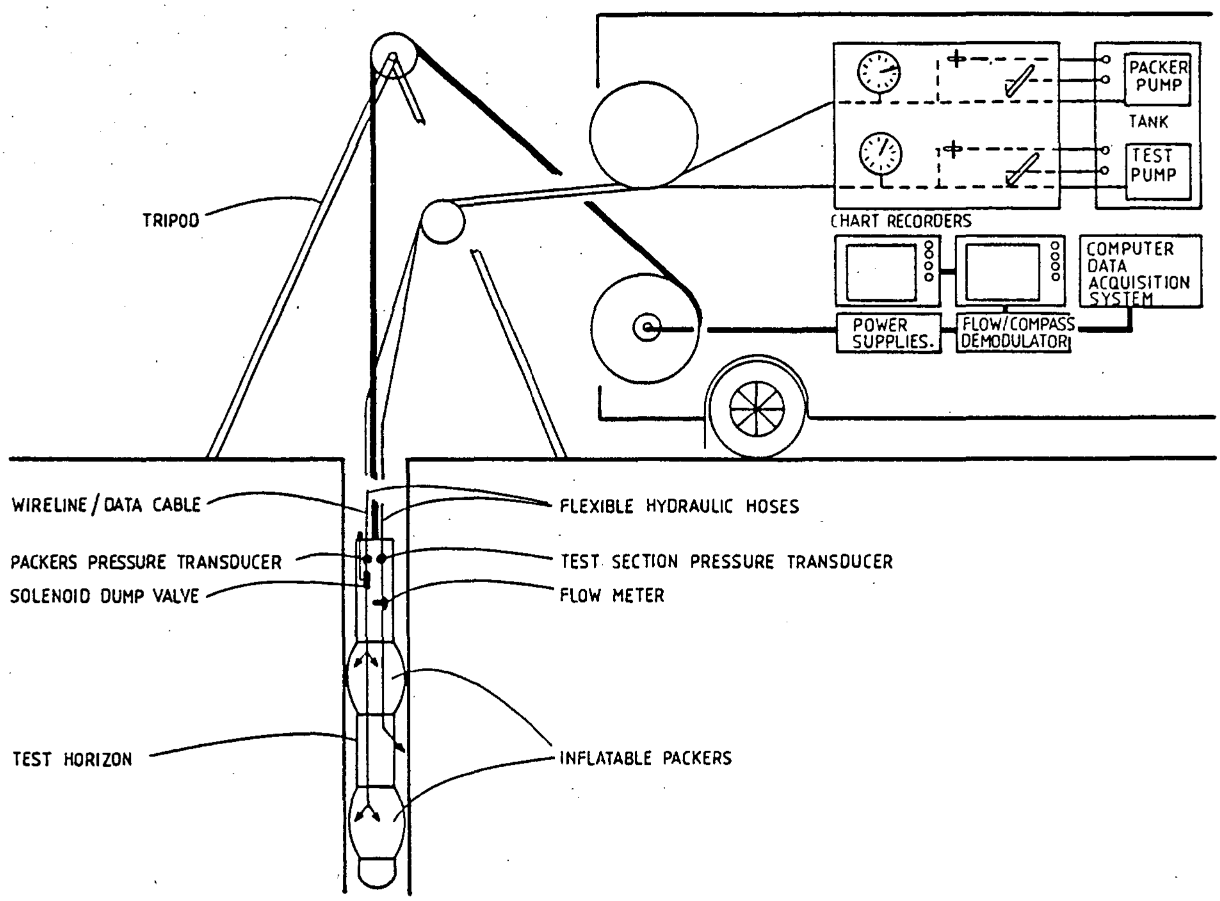
3) Such measurements can be influenced by topographic effects including variations in the cover of weathered material (Denham and Alexander, 1981).

In view of these factors, it was decided to substitute a stress measurement program based on hydraulic fracture because this technique offers the opportunity of making in-situ stress determinations at much greater depths in fresh tectonically-coupled rock. The application of hydraulic fracturing to the stress measurement program in hard rocks has drawn on extensive experience with hydrofracture obtained by CSIRO in sedimentary basin rocks (see for example, Enever and Wooltorton, 1983) and hence, the design philosophy of the down-hole tools and the instrumentation that is reported here is broadly similar to that used previously by CSIRO.

The initial work with the hydrofracture system has been carried out at three sites: Berrigan (NSW), Lancefield (Vic) and Wongan Hills (WA). At each of these sites overcoring measurements had previously been made in the relatively fresh, high modulus rock which outcrops at the surface.

2. Equipment

A hydrofracture system, comprising a fracture tool and an impression tool, has been designed and constructed specifically for this work. Figures 1 and 2 show the essential components of the fracture tool, together with the handling system and the up-hole hydraulic and electronic equipment. The tool is connected to the surface control system by means of two flexible high pressure hoses and a seven conductor armoured co-axial cable. The former allow independent connection of the sealing packers and the isolated test interval (horizon) to separate hydraulic pumps housed in the control vehicle, while the latter provides the necessary electrical and mechanical connections. Important components of the fracture tool include two transducers for the measurement of pressure in the packers



<u>Figure 1</u> Schematic diagram of the hydrofracture system.

Figure 2a The fracture tool, handling system and hydraulic components.

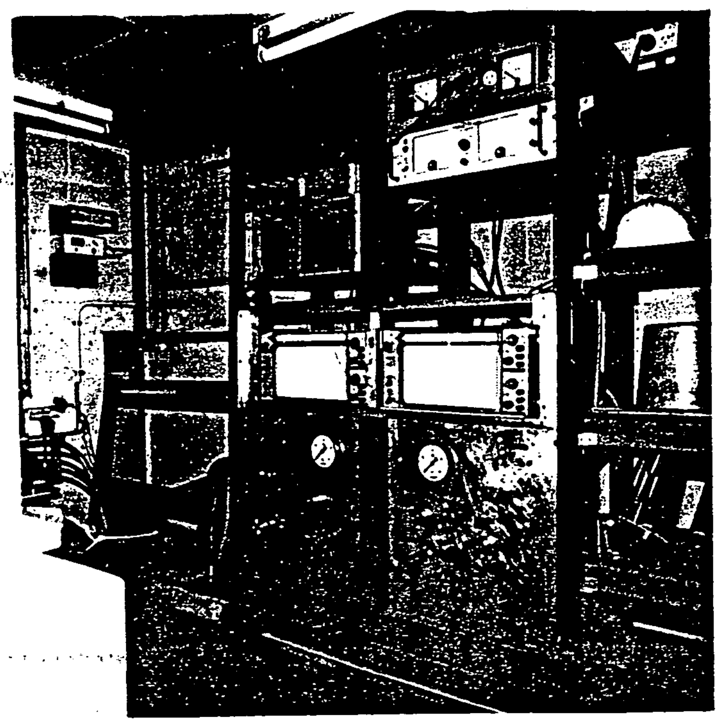


Figure 2b The interior of the truck-borne instrument cab showing the hydraulic and electronic controls.

and the test interval, a flow meter for the measurement of fluid movement into or out of the test interval, and a solenoid operated dump valve to permit effective deflation of the packers at the end of the tests. The length of the test interval can be varied to suit test conditions by using different length spacers (currently 0.5 and 1 metre spacers are used).

The impression tool used in conjunction with the fracture tool includes a digital compass which provides an up-hole display of the tool's orientation in the hole. This arrangement provides a reliable means of determining the orientation of the induced fractures at the borehole wall.

3. Experimental Procedures

The hydrofracture field tests have been carried out at each site in a similar fashion. Water has been used as the fracture fluid and the rates of pressurisation have been relatively slow (approximately 5MPa per minute). The field test procedure followed has involved an initial fracturing phase followed by a number of cycles of pressurisation and subsequent venting of the test interval. The initial fracturing is accomplished by concurrently but independently increasing the pressure in the packers and the test interval. In this way a small positive pressure differential can be maintained between the packers and the test interval which helps confine the fluid in the latter. Pumping is stopped as soon as a crack is formed in order to preserve the initial geometry and to allow a first shut-in pressure to be recorded. The test interval is then vented to atmosphere to allow the induced crack to close. A build-up of pressure in the test interval upon temporarily sealing the system during venting ("pressure rebound") is taken as evidence of continued flow of water out of a closing crack. Venting is continued until this phenomenon ceases.

Further cycles of pressurisation and venting are used to determine the crack re-opening pressure and to gauge whether the orientation of the crack changes as it is propagated. Such a change of crack orientation is reflected in systematic changes in shut-in pressure from cycle to cycle. Crack re-opening pressure is determined with the aid of the down-hole flow meter.

4. Test Sites

In this record, discussion will be limited to three of the sites where hydrofracture stress measurements have been made in granitic rocks (see Figure 3). These sites characterise two different types of results we have obtained in our stress measurement program, both in terms of the form of the pressure-time data recorded and the nature of the fractures produced. These sites are also of particular value because independent estimates of the deviatoric stress state are available from overcoring measurements made nearby (less than 10m laterally distant). These sites are :

1) Berrigan, New South Wales

   The measurements were made in a borehole drilled in a granite of Upper Silurian age at depths between 4 metres and 167 metres. The borehole is located in a small disused quarry in flat lying country in southern New South Wales on the western flank of the Lachlan Fold Belt. The quarry is located at grid reference CD931510 on the 1:100,000 Berrigan Topographic Sheet. The granite is a coarse grained rock with an average grainsize of 1670 microns (as determined from thin section by the linear intercept method of Exner (1972) using a sectioning correction factor of 1.5) which contains crystals of orthoclase of up to 2 cm. In thin-section the rock is seen to be essentially free of deformation induced microstructures other than a few non-pervasive microcracks which are located principally along grain boundaries. Ample evidence in the form of pop-ups and stress controlled jointing exists in the Berrigan area which suggests that the ground is currently being subjected to a strong horizontal compressive stress field. This is of particular interest because the area has a history of seismicity with a magnitude 5.5 earthquake recorded in the vicinity in 1938.

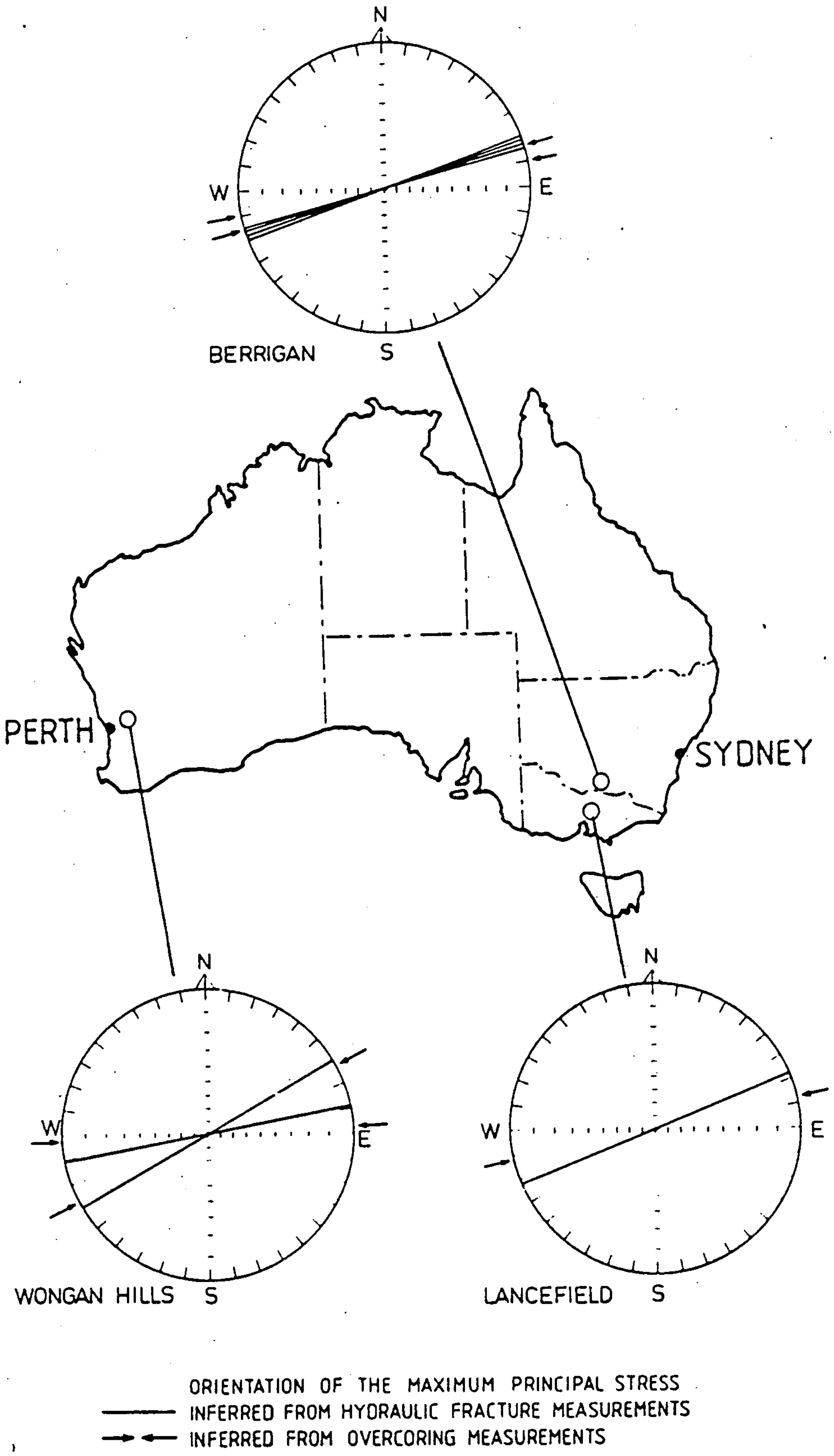


Figure 3 Location map showing the test sites and the orientation of the maximum principal stress as deduced from hydrofracture and overcoring measuremnents.

2) Lancefield, Victoria

This site is located in a broad valley in gently rolling country near the town of Lancefield approximately 75 kilometres north of Melbourne at 37^{o} 11'S latitude and 144^{o} 45'E longitude. The borehole penetrates a fine grained undeformed graniodiorite of Upper Devonian age with an average grainsize (determined as above) of 1440 microns. This site is located within the Lachlan Fold Belt. The hydrofracture measurements were made at this site at a depth of 10 metres.

3) Wongan Hills (Cousin's), Western Australia

This site is approximately 150 km north-east of Perth and within an area bounded by the towns of Meckering, Calingiri and Cadoux, the sites in recent years of earthquakes of magnitudes 6.9, 5.9 and 6.5 respectively. This area is part of the Yilgarn Block, a multiply deformed Archaean craton. The borehole is sited at latitude 30.87^{o} S, longitude 116.96^{o} E. The rock penetrated by the borehole is a deformed rock of granodioritic composition which has probably undergone recrystallisation during its deformation history and is now relatively fine grained. The average grainsize determined from thin-section is 980 micron. The hydrofracture test results discussed here are reported in detail elsewhere (Denham et al, 1986 in prep.).

5. Results of Field Tests

Vertical hydraulic fractures were initiated during testing at each site. At Berrigan, the fractures were found generally to correspond with the test interval, extending at each end into the regions occupied during testing by the packers. In contrast, at the Lancefield and Wongan Hills sites the fractures were found to be restricted to the zone occupied during testing by one or other of the inflatable packers. The orientations of the fractures induced at the three sites are shown in Figure 3.

Also shown in Figure 3 are the corresponding orientations of the major horizontal stress component determined by overcoring tests at each site. For all these sites, the agreement of orientation between the overcoring and hydraulic fracturing stress measurements can be considered good, if the orientation of the induced fracture is taken to represent the orientation of the major horizontal stress component. This is true irrespective of whether the induced fracture formed in the test section or under the packers.

The difference in the locations of the fractures induced at Berrigan compared to Lancefield and Wongan Hills was reflected in the form of the pressure records obtained from the respective sites. Figure 4a is typical of the pressure records obtained for the majority of the tests conducted at Berrigan (i.e. excepting the test at 4m depth). This record exhibits a distinct and sharp crack initiation, well-defined and consistent shut-in pressure for successive cycles of pressurisation and noticeable pressure "rebound" during venting of the test section between cycles. The data in this figure also display clear indications of crack re-opening during the repressurisation cycles (defined by the onset of measureable fluid flow through the down-hole flow meter) and point to a fairly constant fluid pressure during crack propagation. In these respects, the data of Figure 4a might be considered a "text-book" example of a hydrofracture test.

Analysis of the Berrigan field data has in each case been based on the conventionally accepted use of shut-in pressure as the minor horizontal stress component (σ_h) and crack re-opening pressure for calculation of the magnitude of the major horizontal stress component (σ_H). It has also been assumed that these horizontal components of the stress field are principal stress components and that the third principal component (σ_3) is therefore vertical and coaxial with the test hole. The methods used to select the salient data from the test results are illustrated in Figure 4a. These data are tabulated in Table 1, along with a summary of their analysis based on the relationship:

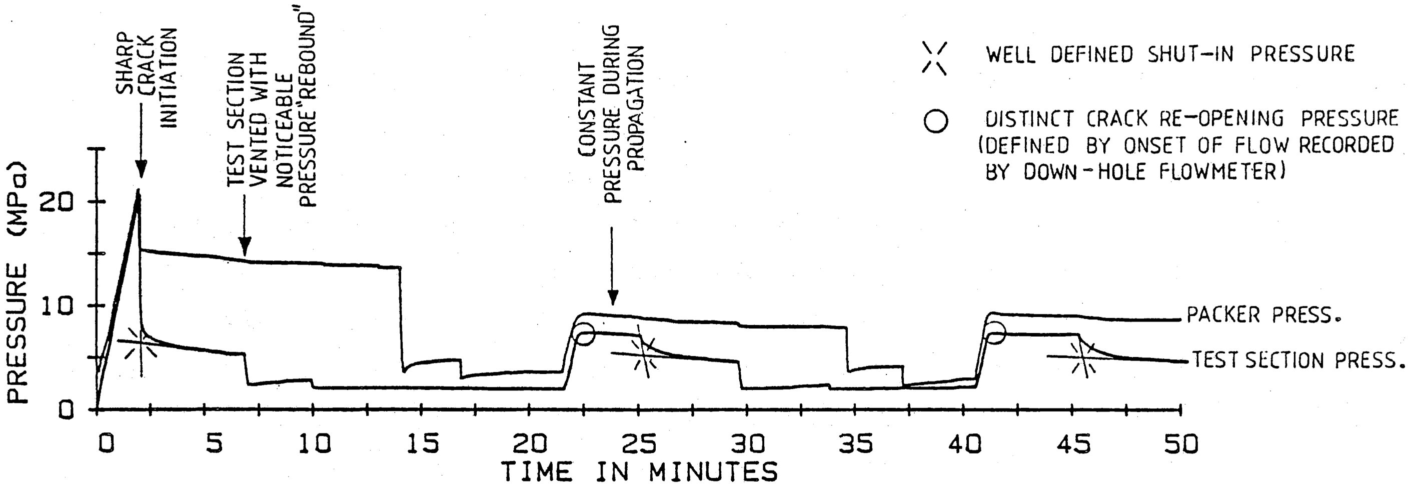


Fig. 4(a).

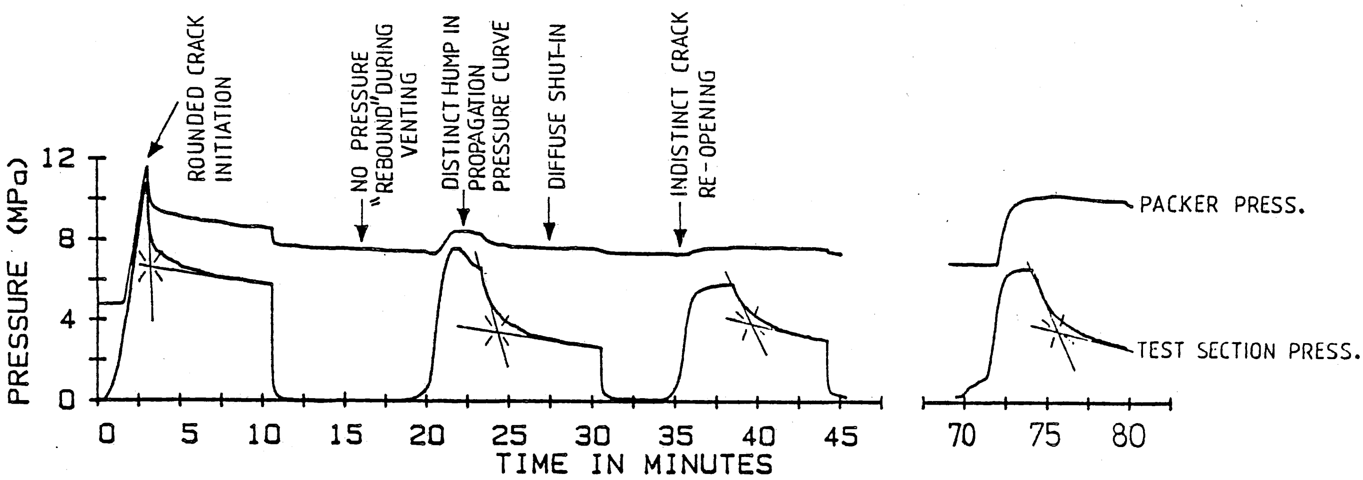


Fig. 4(b).

<u>Figure 4</u> Abridged test records showing the important features and the methods used to extract the data. Fig. 4 (a), Berrigan; Fig. 4 (b), Lancefield.

TABLE 1. SUMMARY OF DATA FOR BERRIGAN SITE

Depth of Test Horizon (m)	Estimated Pore Pressure (Po) MPa	Crack Initiation Pressure (Pi) MPa (Corresponding packer press.)	Range of Shut-in Pressures (1st cycle-nth cycle) MPa	Range of Re-opening Pressures (Pr) MPa	Estimate of σ_2 MPa	Estimate of σ_1 MPa	Orientation of σ_1
4-5	0	11.6 (14.2)	5.6-5.8-6.0	5.7-6.0	5.6-6.0	11.1-12.0	-
69-70	0.7	15.5 (16.2)	5.6-5.5-5.3	5.6-5.5	5.3-5.6	9.7-10.5	70° East of True Nth
100-101	1.0	17.4 (18.9)	6.0-5.5-4.9	6.3-5.6	4.9-6.0	8.1-10.7	75° East of True Nth
125-126	1.3	18.5 (19.7)	6.3-6.2-6.1	6.7-6.7	6.1-6.3	10.3-10.9	70° East of True Nth
154-155	1.5	20.7 (21.5)	6.3-6.1-5.7	7.0-7.0	5.7-6.3	8.6-10.4	72° East of True Nth
168-169	1.7	18.6 (19.0)	7.7-8.0	8.4	7.7-8.0	13.0-13.9	73° East of True Nth
			Results from Overcoring in Adjacent Hole				
3.5					5.6	11.4	74° East of True Nth
3.8					9.5	12.1	80° East of True Nth

TABLE 2. SUMMARY OF DATA FROM LANCEFIELD AND WONGAN HILLS SITES

Depth of Test Horizon (m)	Estimated Pore Pressure (Po) MPa	Crack Initiation Pressure (Pi) MPa (Corresponding packer press.)*	Range of Shut-in Pressures (1st cycle-nth cycle) MPa	Range of Re-opening Pressures (Pr) MPa	Laboratory Strength Range, MPa (Average)	Estimate of σ_2 MPa	Estimate of σ_1** MPa (Average)	Orientation of σ_1
				Lancefield				
approx. 10m	0	10.9 (11.6)	7.0-3.9-3.9-3.9-3.9-3.9	4.6-4.2-4.2-4.2-4.6	10.0-12.0 (11.0)	3.9	10.1-12.1 (11.1)	68° East of True Nth
			Results from Overcoring in Adjacent Hole					
Average of two tests at approx. 10m						3.4	11.0	78° East of True Nth
				Wongan Hills				
66-67	0.7	9.5 (9.6)	6.3-5.1-4.3-4.3	4.2-3.9-3.9	13.2-15.0 (14.1)	4.3	15.9-17.7 (16.8)	79° East of True Nth
69-70	0.7	11.4 (11.5)	5.5-6.1-6.6-6.6	3.9-3.9-4.2	13.2-15.0 (14.1)	6.6	20.9-22.7 (21.8)	60° East of True Nth
			Results from Overcoring in Adjacent Hole					
6.5						3.4	18.2	62° East of True Nth
10.5						6.8	20.4	87° East of True Nth

* Pressure in packers at crack initiation used in analysis
** K = 1.0 used in analysis

$$\sigma_1 = 3.\sigma_2 - K.P_r - (2-K).P_o \qquad (1)$$

(Haimson, 1978)

where: σ_2 is estimated directly from the shut-in pressure

P_r is the crack re-opening pressure

P_o is the ambient pore pressure at the location of the test horizon (based on the assumption that the water table is at the surface)

and, K is a poro-elastic constant which is generally assumed to be equal to 1.

Also included in Table 1 is a summary of the results of the overcoring tests conducted at the Berrigan site.

The data in Table 1 show a high degree of consistency, both in terms of the relatively small ranges observed for shut-in pressure and re-opening pressure for any given test, and in terms of the general agreement between the results for the six hydrofracture tests. There is also good agreement between the hydrofracture tests and the overcoring results.

Figure 4b, containing data obtained from the Lancefield site, is generally representative of the pressure records obtained for the tests at Lancefield and Wongan Hills, and for one test at Berrigan (at approximately 4 metres depth). The distinctive features displayed in Figure 4b include a much more rounded crack initiation phase, more variable and poorly defined shut-in phases and a lack of any detectable pressure rebound during venting of the test section between tests. Crack re-opening is indistinct and significantly, there is a pronounced hump in the first re-pressurisation cycle. All of these features can be linked to the initiation of fracturing under the sealing packers rather than in the test interval.

The less distinct crack initiation and more variable and poorly defined shut-in phases apparent in Figure 4b result from the fluid in the test section having to leak past the inflated packer to enter the crack. This restriction of fluid access results in a dampening of the test interval pressure response. The lack of significant pressure rebound and of a distinct re-opening pressure can be attributed to the propping effect of the packer on the crack initiated under it. The distinct hump in the pressure-time record presumably represents the excess pressure required to extend the original crack along the length of the hole to a position where fluid from the test section can gain direct access to it.

It is also notable in Figure 4b that the pressure responses during the tests subsequent to the first re-pressurisation are very similar. The pressure-time records for the crack propagation phases and the shut-ins are essentially identical. This observation is indicative of the diminishing influence of the original crack location as crack propagation proceeds. The only significant difference between the later cycles is the somewhat higher crack propagation pressure value in the last test. This elevated pressure is linked to the higher packer pressure used in this test and may reflect reduced fluid access to the crack during propagation.

The absence of distinct re-opening pressures for the data obtained from the Lancefield and Wongan Hills sites necessitated the use of a different approach to analysis in these cases. As with the Berrigan data, shut-in pressure was used to estimate the magnitude of σ_2. The magnitude of σ_1 was determined from the relationship:

$$\sigma_1 = 3.\sigma_2 + S - K.P_i - (2-K).P_o \qquad (2)$$

(Haimson, 1978)

where: S is the fracture strength and,

P_i is the crack initiation pressure.

Core recovered from the test holes at the Lancefield and Wongan Hills sites was tested in the laboratory to determine appropriate values of S and K for each site. The outcome of this laboratory testing is discussed in detail in section 6. Table 2 gives a summary of the field and laboratory data for the Lancefield and Wongan Hills sites, and a precis of the overcoring results.

In general terms, the data in Table 2 reflect fairly good agreement between the hydraulic fracture and overcoring results, though the measurements were made at quite different depths. This correspondence is best when the average measured laboratory strength is used. This agreement is evidence of the reliability of both methods of stress measurement and of their ability to determine the in-situ stress field. This holds even when the fractures initiate under the packers, provided that the crack initiation pressure and laboratory measured strength are used in the analysis rather than the re-opening pressure. Scrutiny of the data in Table 2 suggests that use of re-opening pressures would in all cases however have led to serious under-estimations of the value of σ_1.

It would appear from the data contained in Table 2 that when crack re-opening occurs, it does so at a pressure closer to the value of σ_2 rather than the value of $3\sigma_2 - \sigma_1$ as generally assumed for the analysis of crack re-opening pressures. This divergence from normal behaviour may be due in part to the tendency of the packers to hold the cracks open. Alternatively, the low re-opening pressures at the Lancefield and Wongan Hills sites may result from the particular stress states existing there. In both these cases, the net horizontal stress fields tend toward a situation where $\sigma_1 \geq 3.\sigma_2$. Under such a stress state, it might be expected that a crack, once initiated in the borehole wall, would not reclose with depressurisation.

The other notable feature of the data contained in Table 2 is the larger range of shut-in pressures found at the Lancefield and Wongan Hills sites than were found at Berrigan (Table 1). This greater scatter can probably be attributed to variations in the influence of the inflated packer on fluid access to the crack as each test proceeds. Since, as already discussed, the influence of the packer decreases as the crack is propagated further however, it follows that shut-in pressures in the later pressure cycles of a test are likely to be provide more meaningful stress estimates.

6. Results of Laboratory Tests

The core samples from the Lancefield site were all tested without external load. This testing strategy was chosen in order to simulate the stress condition in the borehole wall during the hydrofracture

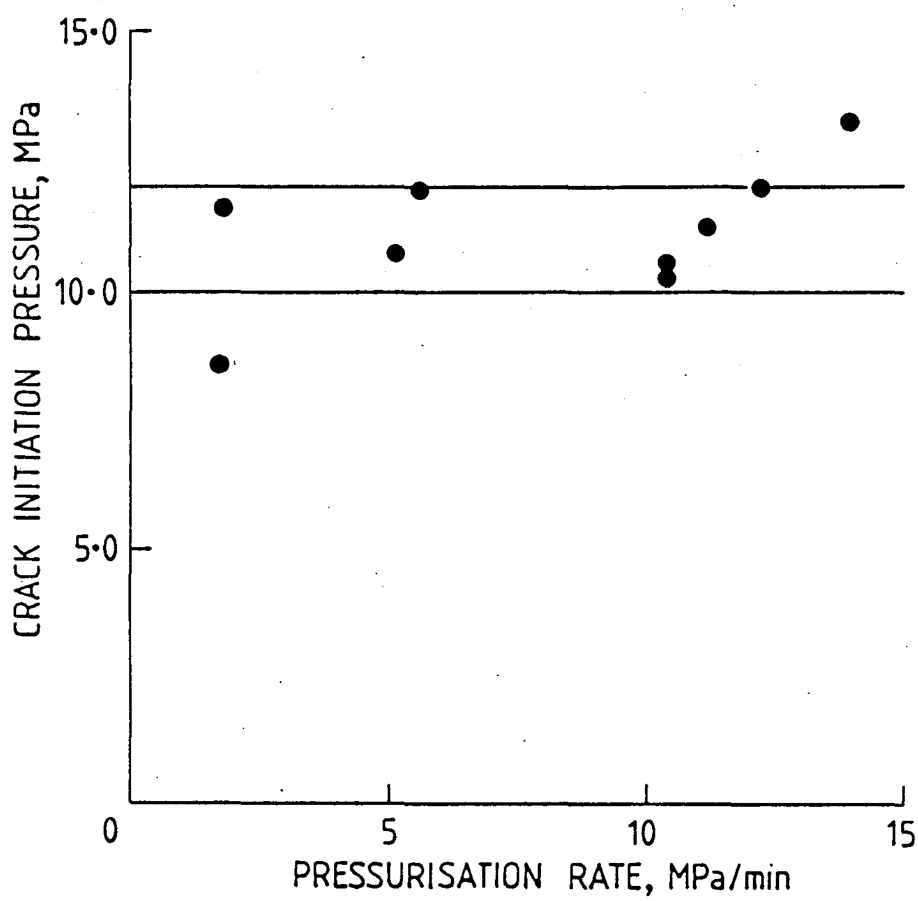


Figure 5 Summary of the laboratory results for the Lancefield granodiorite (see text).

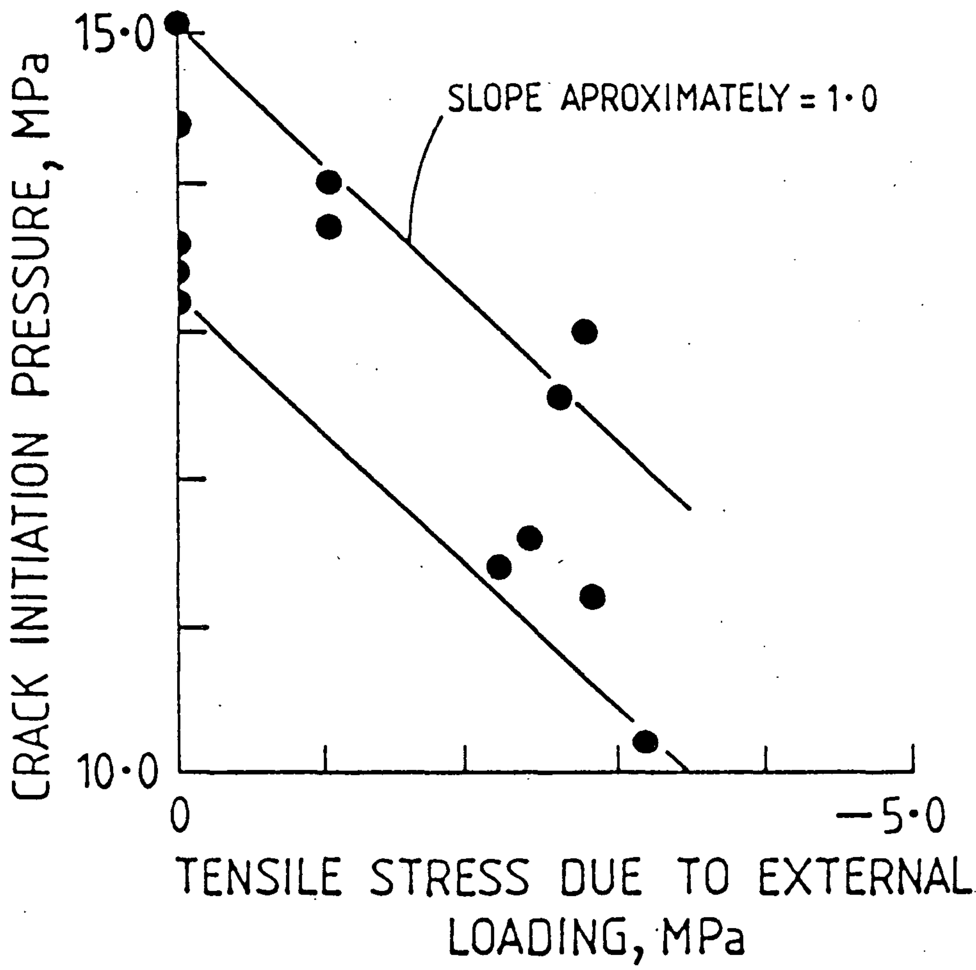


Figure 6 Summary of the laboratory results for the Wongan Hills granodiorite (see text).

testing (i.e. $\sigma_1 \simeq 3.\sigma_2$ in equation (2)). The results of the these tests which are presented in Figure 5, do not suggest a systematic variation of crack initiation pressure with the rate of pressurisation used in the tests. The limits of strength used in the analyses of the Lancefield field data are indicated by the horizontal lines in the figure. In the absence of specific laboratory data, a value of K = 1.0 was assumed for the analyses, based on general practice (Haimson, 1978).

In the case of the material from the Wongan Hills site, samples were tested under external diametric loading in order to produce a net tensile stress at the point of crack initiation in the interior of the samples. This procedure was used in order to simulate the <u>in-situ</u> stress field existing during the hydrofracture experiments which produced a similar circumferential tension in the borehole wall at the location of crack initiation (i.e. $\sigma_1 > 3.\sigma_2$). Figure 6 illustrates the results of these laboratory tests on the Wongan Hills material. Crack initiation pressure is plotted here against the calculated uniform transverse tensile stress existing a short distance away from the central hole in the specimens as a result of the external diametric loading (Jaeger and Hoskins, 1966). The data in Figure 6 are not inconsistent with an approximately linear relationship between crack initiation pressure and tensile stress and fall within a reasonably well defined band. The trend of this band is adequately described by a value of K = 1 ± 0.25 (from equation (2) with $3\sigma_2 - \sigma_1$ assumed equal to the tensile stress and $P_o = 0$). The customarily used value of K=1 was used in the analysis of the Wongan Hills field data, together with the strength measured from the samples tested without external loading (see Figure 6).

7. Discussion

The most obvious aspects of the field results evident from the data contained in Figure 3 and Tables 1 and 2 are the apparent orientational consistency of the horizontal stress field over vast distances (probably coincidental) and the suggestion, based on the Berrigan and Wongan Hills data, of a small systematic gradient in the horizontal stress magnitudes with depth (see Figure 7). The overcoring results from all three sites indicate that the near surface layers are well-coupled to the tectonic basement.

From the viewpoint of the hydraulic fracturing technique, an interesting feature of the experience gained at the three sites has been the variation in the location of the induced fractures relative to the tool geometry (i.e. under packer versus in the test interval) and the commensurate implications on analysis of field data in general. While the practical implications of crack location have been treated above, the factors influencing the variation warrant further discussion.

Two different explanations for the differing locations of crack initiation are suggested by the results presented in this record, viz. control of crack initiation by the petrophysical properties of the rocks at each site, and control by the prevailing stress fields.

1) Petrophysical control

For the field tests conducted at Lancefield and Wongan Hills, the packer pressure during initial pressurisation was kept only marginally above the test interval pressure. Thus at crack initiation, there was only a very small excess pressure in the packers. The most plausible petrophysical explanation for the fracturing to have initiated under these packers then is to suppose that the value of the poro-elastic constant K must have been very close to 1. If the value of K had been significantly above 1, cracks would have been expected to have formed preferentially in the test section where the rock was exposed directly to the influence of fluid penetration. It is notable that a value of K $\simeq 1$ is also consistent with the results of the laboratory tests carried

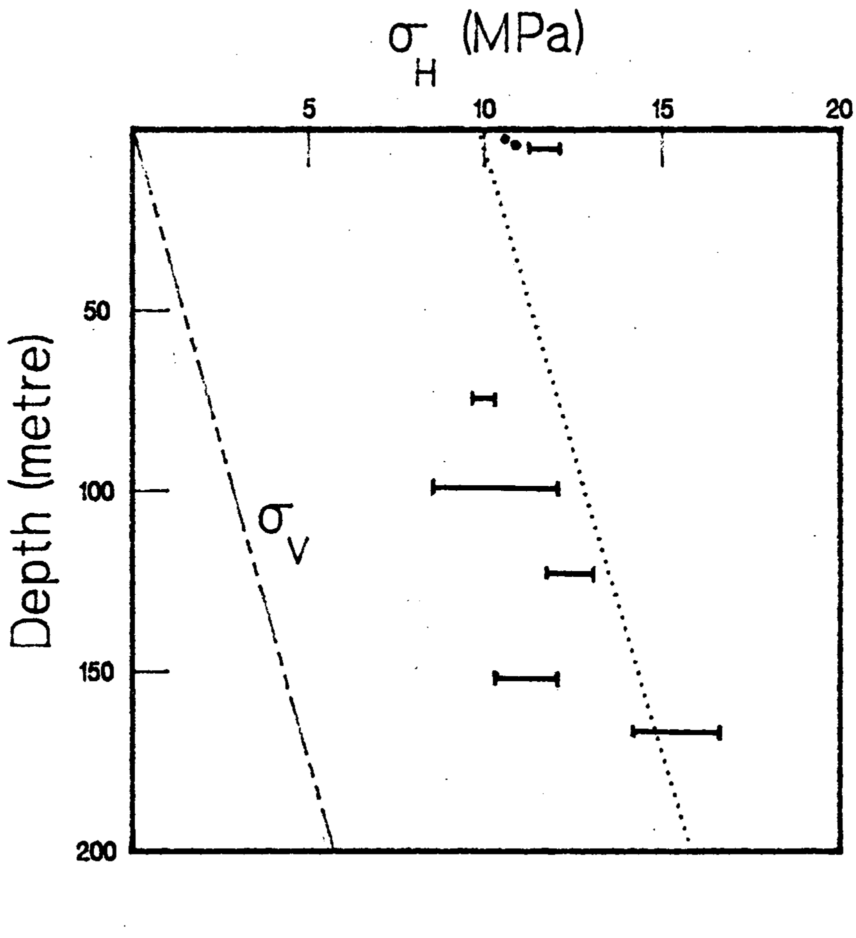


Figure 7 Plot of Maximum horizontal principle stress versus depth at Berrigan, NSW

|—| hydrofracture results

• overcoring results

σ_V vertical stress due to gravity out in the tensile stress regime with this material.

In contrast to the situation at the other two sites, at Berrigan even though the packer pressure during the initial pressurisations was allowed to exceed the test interval pressures by on average 0.9 MPa in the deeper tests, cracks still initiated preferentially in the test sections. It was only when the packer pressure differential was allowed to reach 2.6 MPa in the test at 4 metres depth that crack initiation under the packers resulted. These field observations suggest that the value of K for the Berrigan material might be somewhat greater than 1. This conclusion will be tested in a forthcoming series of laboratory experiments.

2) Stress control

The alternative explanation for the differing locations of the crack initiations rests on the observation that the prevailing in-situ stress field at Berrigan is very different from that recorded at the Lancefield and Wongan Hills sites. At Berrigan, the state of stress in the rock is such as to produce a net circumferential compression in the borehole wall. In contrast, at the other two sites the stress fields are characterised by a net circumferential tension (Wongan Hills) and an approximately zero circumferential stress (Lancefield). These differences may imply somewhat different failure criteria in stress fields with very large stress ratios (i.e. $\sigma_1 > 3.\sigma_2$) compared with more balanced stress fields such as at Berrigan (i.e. $\sigma_1 < 3.\sigma_2$).

Further work is now being undertaken to determine the nature of the mechanism controlling the site of crack initiation in the hydrofracture tests. The ultimate aim of this work is the development of a criterion of failure which will permit better control of crack initiation during hydrofracture testing.

8. Conclusions

The results of the hydraulic fracturing tests conducted to date have established close agreement with earlier measurements of the magnitude and orientation of the in-situ stress field made using the overcoring technique. This correspondence suggests that both methods have the ability to provide useful measurements of the prevailing in-situ horizontal stress field in granitoids.

Two distinct forms of hydraulic fracture initiation have been identified:

1) fracture initiation occurring in the isolated test interval
2) fracture initiation occurring under one or both of the inflatable sealing packers.

Distinctly different styles of pressure records are associated with these two cases. In both instances it has been shown that it is possible to undertake satisfactory analysis of the data. When fractures initiate in the test interval and the net circumferential stress in the borehole wall is compressive, crack re-opening pressure provides a reliable means of estimating the maximum horizontal principal stress magnitude. When fractures initiate under packers and/or the net circumferential stress in the borehole wall is tensile or near zero, crack initiation pressure and the laboratory measured strength can be used to evaluate the major horizontal principal stress magnitude. In both cases the shut-in pressure provides a reliable estimate of the minimum horizontal principle stress magnitude.

The incorporation of a down-hole flow meter in the hydrofracture system has greatly improved the reliability of determination of crack re-opening pressure.

9. Acknowledgements

The equipment used for the field work was designed and developed by J. Edgoose of the CSIRO Division of Geomechanics. His considerable contribution to the program is gratefully acknowledged. Personnel of the Engineering Services Unit, BMR were responsible for the construction and commissioning of the down-hole tools, electronics and handling systems. Particular thanks are due in this regard to R. De Graaf, E. McIntosh, D. Foulstone and A. Sholtez.

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