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HYDRAULIC FRACTURE STRESS MEASUREMENTS AT THE S. GIACOMO POWER STATION - ITALY

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ABSTRACT: The paper describes the results of a programme of Hydraulic Fracture stress measurements conducted at the site of the S. Giacomo power station, in Italy. The tests chamber was located at the planned cavern site in a sequence of marls, with well developed bedding dipping at approximately 45 degrees. The tests were performed in holes oriented on the basis of the results of previous "Doorstopper" measurements.

The aim was to achieve complete resolution of the three-dimensional stress field by means of a combination of the data obtained from the various holes. A description of the equipment employed for the in situ and the subsequent laboratory tests is given. Emphasis is devoted to the testing procedures and to the data interpretation.

The following conclusions are reported: a) the stress field revealed by Hydraulic Fracturing appears consistent with the regional geology of the area, but without any evidence of a direct relationship between the orientation of the stress field and the disposition of the bedding planes intersecting the testing site; b) the stress field revealed by Hydraulic Fracturing is in reasonable agreement with the results of previous "Doorstopper" measurements in terms of orientation, and in good agreement in terms of magnitude (especially for σ_1 and σ_3).

INTRODUCTION

The impact of the relatively complex geological structure typifying Italy on the in situ stress field has been demonstrated by the results of "Doorstopper" measurements made over the last fifteen years [1]. The information presently available in Italy on the state of stress in the earth's crust does not allow satisfactory conclusions to be drawn on possible relationships between the stress field and the geological setting. The need to obtain reliable data on in situ stresses as input to the design of important underground structures (hydroelectric projects and deep tunnels in the Alpine and Appennines regions) is becoming very clear.

In most cases, the assumption of geostatic conditions has been shown to be misleading, requiring that direct measurements be made. Experience with the "Doorstopper" technique has demonstrated shortcomings when relying on a knowledge of the stress-strain properties of the rock for analysis. This has led to an evolving interest in the Hydraulic Fracture technique of stress measurement for applications in relation to the design of underground excavations [2].

The Hydraulic Fracturing technique [3] is not affected by the disadvantages mentioned above. The equipment necessary to conduct tests in the depth range of interest in civil engineering projects need not be very sophisticated. Together, these factors prompted commencement of a research programme on Hydraulic Fracturing, oriented to stress measurement for rock engineering purposes. The research activities were initiated jointly by the Hydraulic and Structural Research Centre of the Italian Electricity Board and the Rock Mechanics Division of ISMES. Initial emphasis was given to laboratory testing on rock specimens (cylindrical shape) and on modelling material (cubic shape) [4]. More recently, a programme of in situ tests has been conducted at the site of the S. Giacomo power station, where the results of "Doorstopper" measurements were available for comparison. This work was conducted jointly with the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia) Division of Geomechanics.

This report describes the experimental details and the results of the programme of Hydraulic Fracture stress measurements conducted in a test chamber at the site of the S. Giacomo power-station.

GEOLOGICAL ASPECTS AND TESTING PROCEDURES

The S. Giacomo site is located approximately 18 km west of Teramo in the foothills of the Appennino Mountains. The specific brief was to determine the three-dimensional stress field by a series of Hydraulic Fracture tests conducted in an array of holes drilled from an underground test chamber.

The test chamber was located at the end of a tunnel approximately 2 km long and under approximately 600 metres of cover. The chamber (4 metres by 4 metres by 3 metres high) was located in a sequence of impervious marls, with well developed bedding dipping at approximately 45 degrees. Calcite veins were an obvious feature, predominantly along bedding. The material was generally competent, but with a pronounced tendency to break-up along bedding planes on exposure to the atmosphere.

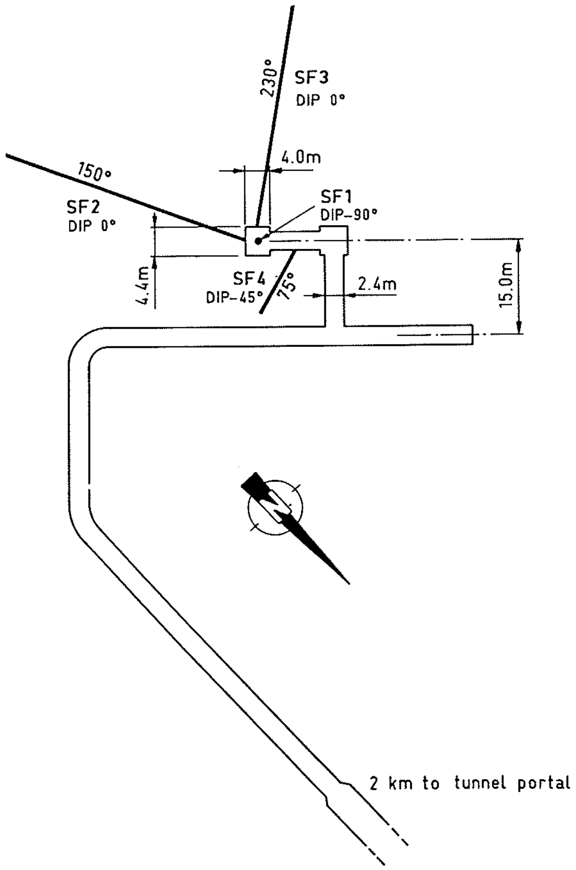

Fig. 1 - Site plan showing orientations of test holes

Tests were conducted in a total of four holes (SFl, SF2, SF3 and SF4). The orientations of the holes are shown diagramatically in Figure 1.

Holes SFl, SF2 and SF3 were drilled prior to the commencement of the test programme to a nominal diameter of 60 mm and depth of approximately 20 m. The orientations were based on the orientations of the principal stresses determined from previous Doorstopper measurements conducted at the site.

The cores from holes SFl, SF2 and SF3 were very broken, making it difficult to select test horizons (Figure 2). A borehole TV camera was used to inspect the holes to aid in test horizon selection.

A further hole (SF4) was drilled during the period of the test programme, to complement the other holes. Hole SF4 was drilled to a diameter of 63 mm and depth of approximately 12 metres. The core from hole SF4 was much better than for the other holes.

Fig. 2 - Typical core: hole SFl (10÷20 m)

Selection of test horizons was ultimately based on core inspection, by giving preference to the most intact sections of core; although in some instances successful tests were conducted in sections of the holes corresponding to poorer sections of core.

Some problems were encountered with the two horizontal holes (SF2 and SF3). These holes were appreciably oversized and oval shaped, particularly closer to the hole collars. This proved to be a problem during the testing programme, particularly in hole SF3, contributing to difficulties in obtaining satisfactory impressions. For this reason, a supplementary hole (SF4) was drilled in a direction oblique to the orientation of the stress field deduced from the Doorstopper results.

The equipment employed for the experimental work has been used by CSIRO for a large number of measurements made from underground openings [5]. The "fracture tool" consists of two packers, approximately 0.33 metres long by 57 mm diametre. The two packers are arranged in a straddle configuration with a 0.33 metre test interval isolated between them. The packers are inflated simultaneously but independently to the test interval. Two flexible hydraulic hoses attached to the tool facilitate independent pressurization of packers and test inteval. A simple set of tubular rods provides for placement of the tool.

Matched hand pumps have been used with this particular system, giving very good control of flow and pressurization rate. Pressure transducers inserted in the "packer" and "test line" provide a continuous record of both pressures throughout a test. The transducer outputs were recorded on a two channel recorder, on the same time base. This facilitated operational control of the test, providing a continuous check on pressurization rate and on the margin between packer pressure and test interval pressure. The use of low viscosity oil, together with relatively low flow rates, ensured that the pressure loss from the point of measurement to the point of interest was minimal.

The experimental procedure involved simultaneous pressurization, at a constant pressurization rate, of packers and tests interval, maintaining an approximately constant pressure margin between packers and test interval, until fracture initiation occured. The excess packer pressure (over the test interval pressure) was maintained at a minimum (usually 1÷3 MPa), commensurate with isolating the fluid in the test interval. By keeping the pressure margin at a minimum it was possible to ensure that the potential error in interpretation of crack initiation pressure was kept to a minimum, regardless of where the fracture initiated (within test interval or under one or the other packer). Apart from minimizing pressure losses, relatively slow pressurization rates ensure that if fracture initiation occurs under a packer, the fluid from the test section has ample time to leak into the crack and this fact will be reported as a pressure drop in the test section, before the pressure increases excessively above the initiation pressure.

Relatively slow pressurization rates also minimize the potential for cracks to change their orientation during the first pressurization cycle [6]. This maximizes the chance of obtaining an initial shut-in pressure representative of the fracture orientation as seen at the hole wall. A pressurization rate of approximately 3.5 MPa/minute was used for the current programme.

Pumping was immediately stopped at the first indication of fracture initiation and the system sealed to allow estabilishment of a shut-in pressure. In the relatively low permeability rock of the S. Giacomo site, the equilibrium pressure was established relatively quickly. Following completion of the first pressurization cycle, further two cycles of pressurization were undertaken to extend the fracture and establish successive shut-in and crack reopening pressures. Between cycles of pressurization the system was drained to allow the initiated crack to close. A build-up of pressure ("rebound") in the test interval when the system is temporarily sealed during draining is diagnostic of a crack having been initiated. This build-up is caused by a continued flow of fluid out of the crack under the action of the prevailing stress. Draining was continued until pressure rebound ceased to occur. This is indicative of the crack being closed and therefore able to be re-opened. The packer pressure was reduced between cycles of pressurization to re-establish the starting conditions prior to a subsequent cycle of pressurization.

Re-pressurization cycles were conducted using the same basic experimental procedure as for the first pressurization cycle. By maintaining a constant flow rate it is possible to reproduce the pressurization rate established during the initial pressurization cycle. Crack re-opening can generally be discerned as the point where the rate of pressurization starts to decrease while maintaining a constant flow rate. Once re-opened, a crack can be extended by continued pumping at the same flow rate (usually at an approximately constant pressure). This allows further shut-in pressures to be established as the crack extends away from the hole. An approximately constant shut-in pressure during successive pressurization cycles is indicative of the crack maintaining approximately the same orientation during propagation. In other instances the shut-in pressure may change substantially from cycle to cycle, reflecting a change in crack orientation. A propagation period per cycle of approximately 10 minutes was adopted for the current investigation.

After completion of the fracture test, an impression packer 1 m long, was used to obtain the orientation of the induced fractures. In operation the impression packer was located in the desired position and the inflated to a pressure somewhere between the corresponding crack initiation and propagation pressures. This ensured that the impression packer did non initiate a "new" fracture.

THEORETICAL CONSIDERATIONS

The classic theoretical understanding hydraulic Fracturing requires the assumption that the test hole be parallel to the direction of one principal stress component. The results of a large number of tests conducted in vertical holes have demonstrated the ability of Hydraulic Fracturing to predict the magnitude and orientation of the secondary principal stress components in the horizontal plane, under the general assumption of one principal stress being vertical or near vertical.

CSIRO experience, based on a number of comparisons with overcoring, has indicated that Hydraulic Fracturing is potentially capable of predicting the magnitude and orientation of the secondary principal stress components in a plane normal to the axis of a test hole, regardless of the orientation of the hole, provided that the hole is oriented approximately parallel to the direction of one principal stress component. It has been found that if the hole is within approximately 20 degress of being co-axial with the direction of the principal stress, an axial or approximately axial fracture will initiate, allowing reliable determination of the magnitudes and orientations of the secondary stress components. This is particularly true if one of the secondary components in the plane normal to the test hole is approximately coincidental with the major principal stress (i.e. hole approximately parallel to the intermediate or minor principal stress component). In the case where a hole is more than approximately 20 degrees from being co-axial with the direction of a principal stress component, it has been observed that fractures often form obliquely to the hole axis, apparently in response to the three-dimensional stress field rather than the stress field in the plane normal to the hole axis [6].

Given that one principal stress component is often vertical, or near vertical, and that the major principal stress is often horizontal or near horizontal, the best way, generally, to approach determination of the three-dimensional stress field is to first conduct tests in a vertical hole (to determine the bearings of the secondary stress components in the horizontal plane) and then to follow-up with tests in horizontal holes drilled in the direction of the bearings of the secondary stress components (based on the information from the vertical hole). The latter tests will provide information on the dips of the principal stress components. Combination of the data obtained from the various holes will then permit complete resolution of the three-dimensional stress field. In the event that the principal stress components are found to be inclined substaintially (say greater than 20°) from horizontal and vertical, a second series of holes can be drilled in the directions indicated by the first set of holes and further test conducted to refine the data.

In the investigation carried out at the S. Giacomo site, logistic considerations required that the holes be drilled prior to commencement of testing. Given that the Doorstopper results indicated a stress field aligned approximately vertically and horizontally, the holes for Hydraulic Fracturing were drilled vertically and horizontally (in the directions of the bearings of σ_1 and σ_2 revealed by the Doorstopper tests). For practical reasons the extra hole (SF4) was drilled in a direction oblique to the orientation of the stress field, even though it was recognized that this might not aid in rigorous specification of the dip of the sub-horizontal principal stress components. It was felt, however, that information from this extra hole could provide an independent check on the analysis based on other holes.

Theoretically, if an axial fracture is initiated during a fracture test, the orientation of the fracture can be taken as the orientation of the major secondary principal stress in the plane normal to the hole axis. The shut-in pressure can be taken as an estimate of the magnitude of the minor secondary principal stress (σ_2'), at right angles to the fracture orientation, in the plane normal to the hole axis. The magnitude of the major secondary principal stress (σ_1') can be estimated from the well known expression [7]:

$$\sigma_1' = 3\sigma_2' + S - KP_i - (2 - K)P_o \qquad (1)$$

where, S is the fracture strength; K is the poro-elastic constant; P_i is the crack initiation pressure and P_o is the ambient pore pressure.

This reduces to:

$$\sigma_1' = 3\sigma_2' + S - P_i \qquad (2)$$

because:

- in the case of tests conducted from underground openings, it is usually justifiable to consider the region of rock in which the tests are conducted (generally less than 20 metres from the wall of the opening) to be drained of any substantial ambient pore pressure;
- for most materials and stress conditions of engineering significance, the value of K can be taken as approximately 1.

Alternatively, σ_1' can be estimated from the expression:

$$\sigma_1' = 3\sigma_2' - P_r \qquad (3)$$

where P_t is the crack re-opening pressure.

Misinterpretation of re-opening pressure can sometimes occur for some stress conditions ($\sigma_1' \geq 3\sigma_2'$, $\sigma_1 \div \sigma_2'$) leading to incorrect estimates of the magnitude of σ_1'. In other cases, however, the use of re-opening pressure can give the most reliable estimate of σ_1', since uncertainties associated with the determination of the appropriate strength are removed.

As a check that the re-opening pressure has been correctly interpreted, the fracture strength implied by the field record ($P_i - P_r$) can be compared with the value determined from laboratory tests. Unless a reasonable match is obtained, it has been found inappropriate to employ re-opening pressure for analysis.

In variable materials the best approach is to determine the strength of each individual test horizon by conducting laboratory tests on samples prepared from the corresponding core. In more uniform materials, and/or in situations where limited material is available for laboratory testing, it may be better to determine a range of strengths representative of the field test horizons, and to compare these with the range of ($P_i - P_r$) values obtained from the field tests. If a general match can be demonstrated, then it is appropriate to employ the re-opening pressures for analysis. This was the approach used in the current instance.

LABORATORY TESTS

Laboratory tests were conducted on representative samples prepared from the more intact sections of core (free of obvious weaknesses) to determine fracture strength. Samples were cut to a length of approximately two to three core diameters from an intact core stick. A small diameter hole was drilled along the axis of each sample to permit internal pressurization. An hydraulic probe was glued into the hole to facilitate pressurization by means of a hand pump. The other end of the hole was blocked by means of a metal plug glued into the hole.

Some samples were tested without any external constraint. In these cases the samples were pressurized internally, using the same oil as employed for the field tests and at a rate of pressurization equivalent to the field tests, until fracture initiation occurred. The fracture initiation pressure was then taken as a direct measure of fracture strength. Fractures were generally axial and oriented in the direction of the strike of incipient bedding planes contained in the samples.

In order to examine the influence of bedding on fracture initiation pressure, a number of samples were subjected to external loading prior to internal pressurization in an attempt to control the direction of fracture initiation to be other than the direction of the strike of bedding. The samples involved were prepared by grinding the end surfaces flat and parallel, and grinding two opposing "flats" on them to permit the application of uniaxial load in the direction normal to the strike of the bedding planes (Figure 3). To ensure that the samples did not fail prematurely during application of the external load, axial constraint was first applied to the end surface.

Some initial tests were conducted to determine the minimum magnitude of external uniaxial load required to ensure that fracture would initiate in the direction of loading, rather than parallel to the strike of the bedding planes, during internal pressurization. Subsequent tests were conducted at various values of external loading (constant during the tests) while internal pressurization was carried out as for the unloaded samples. In the case of the externally loaded samples, the fracture strength (S) was determined by adding together the fracture initiation pressure and the uniaxial tensile circumferential stress produced in the wall of the test hole at the location of fracture initiation by the external uniaxial load. Fractures were universally axial and oriented approximately in the direction of external loading (i.e.: not influenced by incipient bedding). The fracture evident in Figure 3 can be considered as indicative of the potential for fractures to be formed during the field tests in a direction dictated by the stress field rather than by the disposition of incipient weaknesses, at relatively small levels of differential stress.

Table I summarises the results of the laboratory tests conducted on the unloaded and externally loaded samples. The results show a tendency for the fracture strength to be somowhat greater for fractures that initiate other than in a direction parallel to the strike of bedding, compared to fractures parallel to bedding strike. The difference is subtle enough, however, that the respective ranges of values overlap. This observation is consistent with the potential for fractures to develop in a direction controlled by the stress field, rather than by incipient weaknesses, at relatively low levels of differential stress. The most significant difference appears to be between the strength of fractures initiating directly along bedding and other orientations of fracture development. Based on the results from the laboratory testing programme, the strength values ($P_i - P_r$) estimated from the field tests were scrutinized to select tests for further analysis that were consistent with failure occuring through the intact material rather than along bedding.

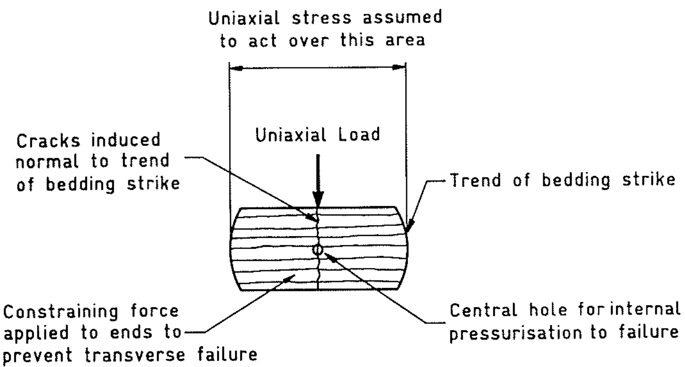

Fig. 3 - Scheme of test sample subjected to external loading to asses influence of bedding

***Table 1:** summary of Laboratory Strength Tests: average values (± standard deviation)*

Type of Failure	N° of Tests	Uniaxial Stress (MPa)	Crack Initiation Pressure (MPa)	Fracture Strength (MPa)
Parallel to strike of bedding	11	0	12.8	12.8 (± 2.4)
Parallel to bedding	2	0	7.6	7.6 (± 0.4)
Not influenced by bedding	16	5.8	8.9	14.7 (± 2.5)

INTERPRETATION OF TEST RESULTS

Figure 4 is typical of many of the pressure records obtained during the testing programme, for cracks that initiated approximately axially, and demonstrates the major features of interest.

The relatively sharp peak pressure and sudden drop in pressure from the peak is indicative of crack initiation occuring within the isolated test horizon. This implies that the appropriate fracture initiation pressure to employ is the peak pressure recorder in the test interval rather than within the packers.

Most tests considered for analysis exhibited this style of behaviour and therefore had the peak tests interval pressure recorded as the crack initiation pressure. In some cases a more gentle drop of pressure from the peak was observable, typical of crack initiation occuring under one or other packer. In this instance the peak packer records generally confirmed the location of fractures as deduced from the pressure record.

In Figure 4 the shut-in stages for both the initial pressurization cycle and subsequent re-pressurization cycles are all very well defined by marked transition from the initial pressure drop to the steady state pressure is symptomatic of the relatively low permeability of the rock, with minimal leakage from the hole/crack system.

The double tangent method of interpretation was employed to obtain the values of shut-in pressure reported here. This method gives the best estimation of the minor stress component magnitude as confirmed by a number of comparisons between hydraulic fracturing and overcoring conducted in close proximity [8].

The approximately constant shut-in pressure from pressurisation cycle to cycle evident in Figure 4 is typical of tests in which an initiated crack maintains approximately the same orientation during crack propagation. In this situation, the long term shut-in pressure can generally be taken as the best estimate of the minor stress component magnitude since it is least likely to be influenced by limited crack extent. In the majority of tests conducted at the site, the shut-in pressure was approximately constant from pressure cycle to cycle, especially the second and third cycles. The long term shut-in pressure was taken in all cases as being most representative of the minor stress component magnitude.

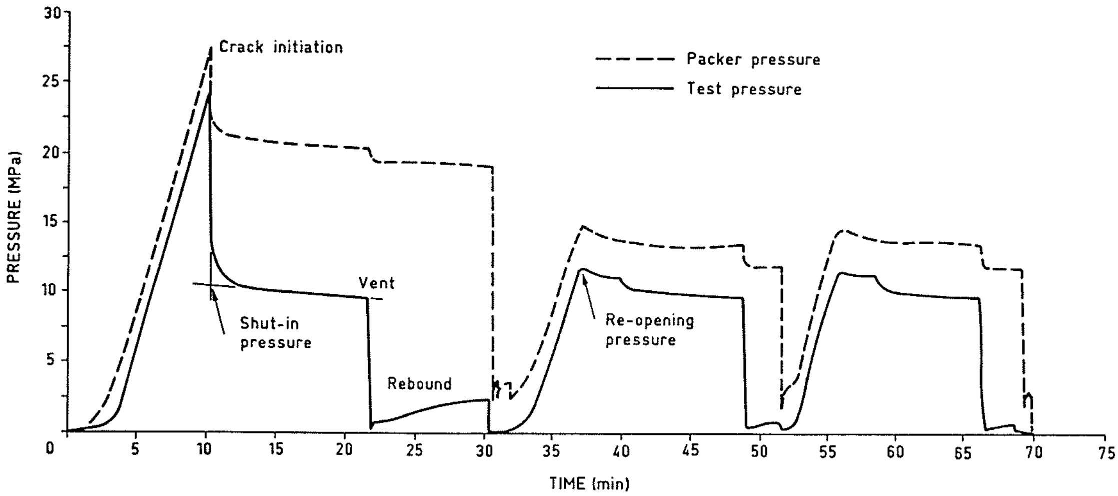

Fig. 4 - Typical pressure record: hole SF4; test 3 (6.3÷6.6 m)

The distinct crack re-opening pressure and relatively constant crack propagation pressure evident during the repressurization cycles in Figure 4 has been found to be diagnostic of a stress field in the plane normal to the hole axis with the two principal stress components having a ratio of magnitudes close to 2:1. Approximately half of the tests considered for analysis exhibited this style of re-opening curve. In other cases, there was a distinct "bump" evident in the re-opening pressure curve during propagation. In some instances this could be related to the development of fractures under one or the other packer. There were cases, however, where cracks clearly initiating within the test interval exhibited this characteristic "bump". It is a general feature that "bumps" in the pressure curves are associated with stress component magnitude ratios significantly less than 2:1. It was also noticeable that in the cases where "bumps" were evident in the pressure records, the drop-off in pressure on completion of pumping during repressurization cycles was significantly more pronounced than in the cases without "bumps". This is also symptomatic of stress ratios less than 2:1.

In all tests, crack re-opening pressure was estimated as the pressure where the pressurization curve deviated from the linear pressurization rate maintained by a constant flow rate.

The interpretation of the test results was based on the following considerations.

For each test an estimate of in situ fracture strength was made by determining the pressure increment between the appropriate fracture initiation pressure and the corresponding crack reopening pressure. Only those field tests having a strength greater than the minimum of the strength range obtained from laboratory tests with external loading were considered for subsequent analysis. Examination of the impression packer records for these revealed that in all cases the induced fractures were approximately

***Table 2:** Summary of Field Test Results*

HOLES	VERTICAL					HORIZONTAL							INCLINED		
					avg.							avg.			avg.
Hole/Test No.	SF1/1	SF1/2	SF1/3	SF1/10	SF1	SF2/4	SF2/5	SF2/10	SF2/6	SF2/11	SF2/8	SF2	SF4/1	SF4/3	SF4
Depth from collar (m)	3.70	4.55	5.25	6.35	—	12.35	14.65	15.25	16.25	17.35	18.45	—	5.25	6.45	—
Initiation Pressure(MPa)	27.6	24.5	23.1	31.0	26.6	26.5	28.9	32.4*	29.6	35.8	26.5	30.0	28.3	24.8**	26.6
Long Term Shut-in (MPa)	10.3	9.9	9.3	11.0	10.1	10.3	10.3	10.3	10.3	13.8	10.3	10.9	10.3	10.3	10.3
Re-opening Pressure (MPa)	11.7	11.7	11.4	13.8	12.2	11.7	13.8	14.1	13.8	18.6	13.8	14.3	11.4	11.4	11.4
σ_2' (MPa)	10.3	9.9	9.3	11.0	10.1	10.3	10.3	10.3	10.3	13.8	10.3	10.9	10.3	10.3	10.3
σ_1' (MPa)	19.2	18.0	16.5	19.2	18.2	19.2	17.1	16.8	17.1	22.8	17.1	18.4	19.5	19.5	19.5
S (MPa)	15.9	12.8	11.7	17.2	14.4	14.8	15.1	18.3	15.8	17.2	12.7	15.7	16.9	13.4	15.2
Orientation of crack looking into hole	in 110°	in 80°	in 60°	in 50°		up 100°	up 120°	up 102°	up 108°	up 114°	up 100°		up 40°	up 44°	
Orientation of crack relative to hole axis	up 17°	up 19°	up 20°	up 15°	in			22°				in			in

* Partly influenced by higher packer pressure (34.5); **Influenced by extension of axial crack from SF4/1.
avg. = average values.

axial (maximum inclination to hole axis of approximately 20°), with an orientation not obviously related to the local bedding.

A summary of the pertinent information, including the orientation of the fractures, for the tests selected for analysis is given in Table II. Comparison of Table II with Table I reveals a reasonable degree of correspondence between the distribution of strengths determined from field and laboratory tests.

Based on this observation, interpretation was founded on the use of re-opening pressure. The results of interpretation are included in Table II.

The tests considered for analysis in holes SF2 and SF4 showed relatively little scatter in terms of fracture orientation. For both these holes fracture orientation did not appear to be directly influenced by the chamber geometry or local geology. This was not the case, however, in the vertical hole, SFl.

The relatively great scatter of crack orientation (110°÷50° as shown in Table II) can possibly be attributed to two causes:

a) the influence of the test chamber on the horizontal stress field orientation at the locations of the lower tests in the hole;
b) the influence of the bedding on fracture orientation.

In regard to the first point, there is a noticeable tendency for the orientation to rotate from approximately normal to the chamber axis lower in the hole to a somewhat more acute orientation (with respect to the axis) higher up. This is suggestive of the influence of the stress concentration effect of the chamber. This is not born out, however, by the respective magnitude of the major secondary principal stress component determined from the tests concerned. The magnitude σ_1' given in Table II for these tests do not show any systematic trend for a decrease in magnitude away from the chamber as might be expected if a significant stress concentration effect were in evidence.

In regard to the second point, the noticeable tendency for the orientation of the uppermost test to approximately correspond to the strike of the bedding suggests the possibility of the bedding having influenced fracture orientation. This is not consistent, however, with the relatively high fracture strength (Table II) determined from the pressure record for the test concerned.

After consideration of these factors, subsequent analysis was based on the compromise procedure of taking the average fracture orientation as being representative of the bearing of the major secondary principal stress in the horizontal plane.

The data contained in Table II has been interpreted to give the magnitudes of the secondary principal stresses in the planes normal to the respective hole axes, based on the assumption that the induced cracks were close enough to axial in all cases to ignore any departure from the ideal situation of fractures initiating axially in response to the secondary stress field in the plane normal to the hole axis. The orientation of the major secondary principal stress in each case was taken as being normal to the respective hole axis, in the direction of the strike of the fracture plane, and that of the minor secondary principal stress as being normal to the hole axis, in the direction normal to the strike of the fracture plane.

To obtain the three dimensional stress field, the secondary stress fields derived from the individual holes, were combined together by the process outlined below (see Figure 5, which is a stereographic summary of SFl, SF2 and SF4 results).

The results from hole SFl were used to asses the bearing of major principal stress based on the results obtained from hole SF2 which indicated an approximately horizontal stress magnitude considerably in excess of the near vertical stress. The average bearing of the major secondary principal stress (σ_1') determined from the tests conducted in SFl can be considered as the bearing of the major principal stress (σ_1') in the three-dimensional stress field. The average magnitude of the major secondary principal stress determined from SFl can be considered as a resolved component of the magnitude of σ_1 in the horizontal plane. Likewise, the minor secondary principal stress (σ_2') determined from the tests in SFl can be considered as a resolved component of the three-dimensional stress field in the horizontal plane. The vertical plane marked in Figure 5 represents

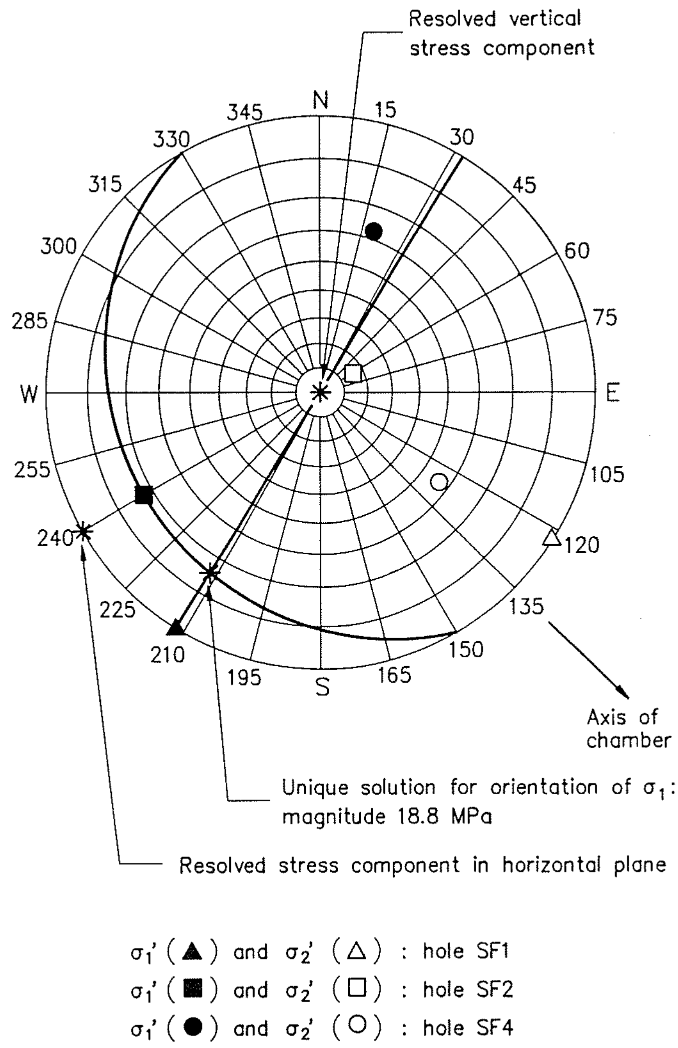

Fig. 5 - Combination of SFl, SF2 and SF4 results (average values of stresses)

the plane in which all solutions for the orientation (bearing and tip) of σ_1 must lie.

If hole SF2 had have been drilled in the direction normal to the bearing of σ_1 as indicated from the results obtained in SFl, then the dip of the major secondary principal stress (σ_1') would have been considered as the dip of the major principal stress (σ_1) in the three-dimensional stress field, and the magnitude of σ_1' determined from SF2 taken directly as a measure of the magnitude of σ_1. In fact, SF2 was oriented approximately 30° from the bearing of σ_1. In this situation, the dip plane including the axis of SF2 and passing through the average dip of the major secondary principal stress obtained from the acceptable tests conducted in SF2 can be considered as the plane containing all solutions for the true dip of σ_1 in the three-dimensional stress field. The average magnitude of the major secondary principal stress determined from SF2 can be considered as a resolved component of the magnitude of σ_1 in this dip plane. The minor secondary principal stress (σ_2') determined from the tests in SF2 can be considered as a resolved component of the three-dimensional stress field in a near vertical orientation.

The only unique solution for the orientation of σ_1 is given by the intersection of the two planes as shown in Figure 5. This represents a solution for the orientation of σ_1 mutually compatible with the conditions dictated by the analyses conducted for holes SFl and SF2. The corresponding mutually comptaible value for the magnitude of σ_1 can be obtained by a series of resolutions of stress components. The resultant value so determined was 18.8 MPa.

Precise definition of the orientations of the intermediate and minor stress components (σ_2 and σ_3) of the three-dimensional stress field would have required results from a third hole, drilled approximately in the direction of σ_1. The inability to get useful results from hole SF3 (drilled relatively close to the bearing of σ_1) precluded the possibility of rigorously completing the definition of the orientation of σ_2 and σ_3. In this instance, however, the magnitudes of the minor secondary principal stresses (σ_2') determined from holes SF1 and SF2 were similar (10.1 and 10.9 MPa respectively) suggesting that σ_2 and $\sigma3$, in the plane normal to the orientation of σ_1, would also be of similar magnitude and therefore make the precise definition of the orientations of σ_2 and σ_3 of little significance.

As an independent check on the analysis described above, the results obtained from the two acceptable tests conducted in hole SF4 can be superimposed. The orientation chosen was directly up the dip of the bedding, promising the possibility of obtaining intact test horizons free of bedding intersecting the hole at an angle. This in fact proved to be the case, with two tests being conducted in rock essentially free of any incipient weaknesses. The orientation of SF4, in hindsight, was approximately equi-spaced from the orientation of all principal stress components (σ_1, σ_2 anf σ_3).

The obvious feature descernable from the superposition of the results of SF4 shown in Figure 5 is the reasonable agreement between the bearing of σ_1' (SF4) and the estimated bearing of σ_1 obtained from holes SF1 and SF2. This lends confidence to the estimated bearing of σ_1. The disparity in dip can be attributed to the constraints placed on the orientation of fracture development by the hole orientation. The average magnitude of σ_1' determined from the tests conducted in hole SF4 (19.5 MPa) is in reasonable agreement with the magnitude estimated from holes SF1 and SF2 (18.8 MPa). Given the disparity in dip, however, a somewhat lower magnitude for σ_1' (SF4) might have been expected. One possible explanation for this lies in the tendency for higher estimates of σ_1' to correlate with stronger test horizons in most cases (Table I); in fact, the rock corresponding to the two tests in SF4 was noticeable stronger than average. The average magnitude of σ_2' obtained from SF4 (10.3 MPa) is in good agreement with the values of σ_2' obtained from SF1 and SF2, and confirms the premise that the intermediate and minor principal stress components (σ_2 and σ_3) lying in a plane normal to σ_1 have approximately the same magnitude (10.1÷10.9 MPa).

The match between the information obtained from SF1, SF2 and SF4 can be improved from its already good degree of correspondence, if the results from SF1 are adjusted for the relatively small amount of inclination (about 18° from axial) of the cracks consistently obtained for the tests conducted in this hole.

The adjustment made to the orientation of σ_2' (SF1) implies a complementary change to the orientation of the plane containing the solution for the orientation of σ_1. This is shown on Figure 6. With this adjustment there is a very close agreement between the results from SF1 and SF4 for the bearing of σ_1. This adjustment results in a slight change to the predicted orientation of σ_1 from SF1 and SF2. The differences between the two solutions are not sufficient, however, to imply any significant differences to the estimates of stress component magnitude outlined above.

Figure 6 represents a summary of the information obtained from the process of combination of data outlined above. The summary is superimposed on the results obtained from earlier "doorstopper" measurements for purpose of comparison.

DISCUSSION AND CONCLUDNG REMARKS

The summary of the data given in Figure 6 illustrates a reasonable degree of correspondence, in terms of orientation, between the stress fields revealed by Hydraulic Fracturing and the "Doorstopper". In terms of the corresponding magnitudes, the following observations can be made:

a) very good agreement for the maximum principal stress σ_1 (18.8 MPa in both cases);
b) reasonable agreement for the minimum principal stress σ_3 (about 10 MPa from Hydraulic Fracturing against 8.4 MPa from "Doorstopper");
c) a significant difference for the intermediate principal stress σ_2 (less than 11 MPa from Hydraulic Fracturing against 17 MPa from "Doorstopper").

With reference to point c), there is no obvious explanation for the difference between the values obtained by means of the two kinds of tests, particularly when considering that the disparity is apparently not uniformly distributed. The only plausible explanation would appear to be the influence of anisotropy of stress-strain properties in the analysis of the "Doorstopper" results. The material was noticeably anisotropic, with a pronouncd tendency to break-up along bedding planes on exposure to the atmosphere.

The magnitude estimated from Hydraulic Fracturing for the vertical stress component (11.5 MPa) is in reasonable agreement with the magnitude of the vertical stress component that can be estimated from overburden loading. The overburden cover at the site is approximately 600 m, which represents a theoretical overburden pressure at the site of approximately 15 MPa. The ratio of measured vertical stress magnitude to theoretical overburden pressure (11.5/15) of 0.8 is in general accord with expectations for the vertical stress beneath ridges in mountainous terrain.

Superimposed on Figure 6 is a summary of the orientation (poles to planes) of the major geological structure (bedding) planes intersecting the site. Only the most dense portions of the distributions of the poles are shown. This superposition suggests the

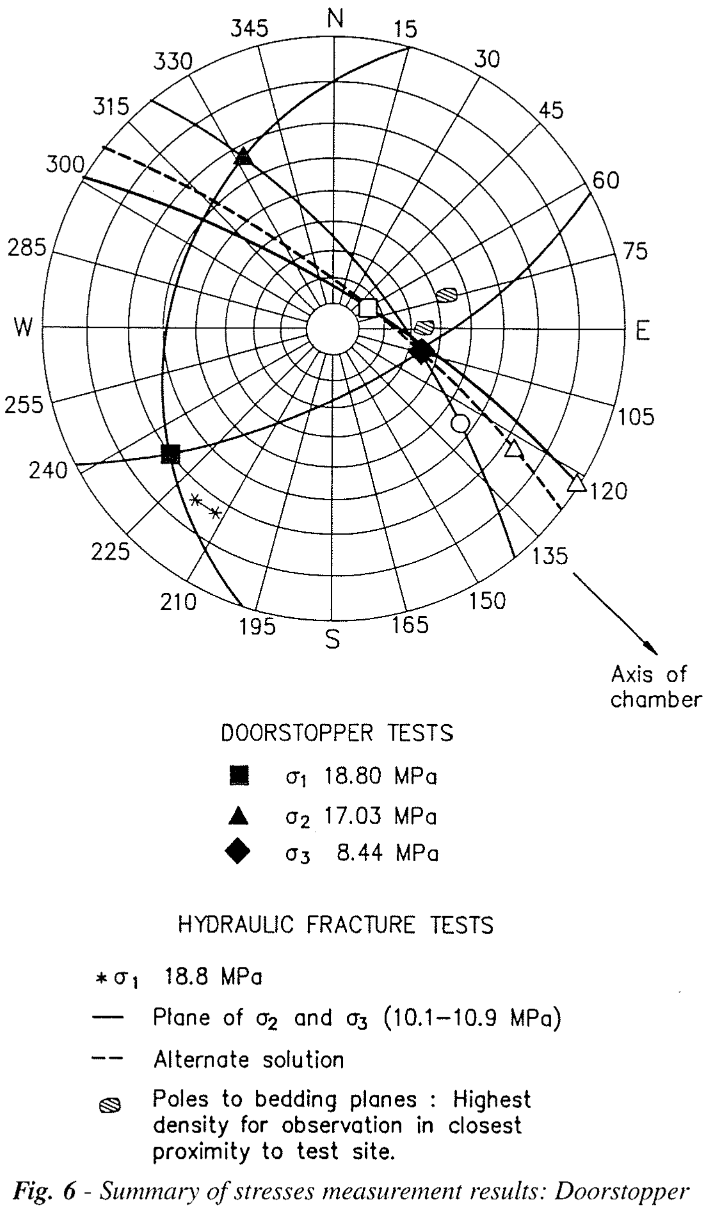

***Fig. 6** - Summary of stresses measurement results: Doorstopper and Hydraulic Fracturing tests*

absence of any direct relationship between the orientation of the stress field and the disposition of the bedding.

The bearing of σ_1 determined from the Hydraulic Fracturing is shown in relation to the orientation of the local topography in Figure 7. There is a suggestion that the orientation of σ_1 may have been influenced, to some extent, by the valley of the Vomano River, the bottom of which is approximately at the same level as the site. The stress concentration effect of the topography is unlikely, however, to have had sufficient influence on the stress field to account for the proponderance of σ_1 as measured.

Figure 7 summarises the regional structural geology of the area. The orientation of σ_1 determined from the Hydrualic Fracturing programme is superimposed. The measured orientation of σ, appears to be reasonably consistent with the orientation of the system of active overthrusts domaniting the structural picture. The significant magnitude of σ_1 determined from the Hydraulic Fracturing is also consistent with this regional picture.

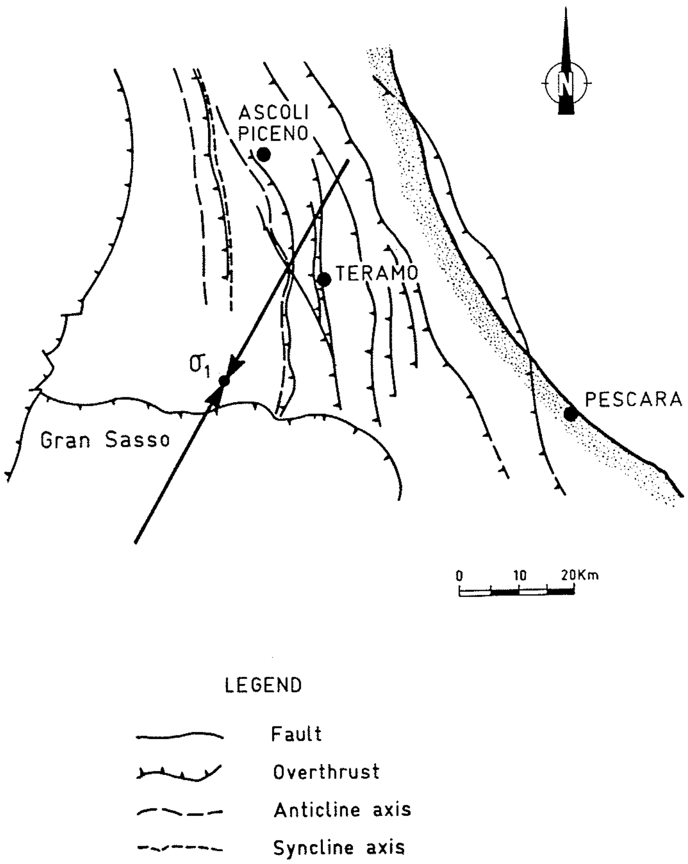

***Fig. 7** - orientation of measured stress field in relation to regional geology*

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