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ISRM Suggested Methods for rock stress estimation—Part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF)☆

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1. Introduction

1. This is Part 3 of four new ISRM Suggested Methods (SMs) for rock stress estimation:

Part 1: Strategy for rock stress estimation
Part 2: Overcoring methods

☆Please send any written comments on this ISRM Suggested Method to Prof. JA Hudson, President of the ISRM Testing Methods Commission, 7 The Quadrangle, Welwyn Garden City, Herts AL8 6SG, UK.

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Part 3: Hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF) methods
Part 4: Quality control of rock stress estimation.

These SMs are published together in a Rock Stress Estimation Special Issue of the International Journal of Rock Mechanics and Mining Sciences, 2003, Volume 40, Issue 7–8, together with a suite of supporting contributions describing various aspects of rock stress estimation. It is strongly recommended that the new SMs be studied in association with the supporting contributions in the 2003 Special Issue—because these contributions provide a wealth of further detail and measurement case examples.

2. Hydraulic fracturing (HF) is a borehole field-test method designed to assess the state of in situ stress in the earth crust. This method is also referred to as hydrofracturing, or hydrofrac, and sometimes as minifrac. The HF stress determination method derives from a technique originally developed by the petroleum industry to stimulate oil production by increasing the overall porosity and permeability of rock. A detailed history of the method and a thorough description of the equipment, setup, test data interpretation and in situ stress derivation are presented by Haimson [1]. An American Society for Testing and Materials standard test method has been available for some time [2]. Successful HF tests result generally in an estimate of the state of in situ stress (both magnitudes and directions) in the plane perpendicular to the axis of the borehole. When both the borehole and the induced HF are nearly vertical, the stress component in the direction of the hole axis is taken as being principal and equal to the overburden weight.

3. The domain of application of the HF method has been extended with the HTPF method [3]. The HTPF (hydraulic testing of pre-existing fractures) method provides an evaluation of the complete stress tensor (6 components), independent of borehole orientation and material properties. When possible, both methods should be combined for optimum results.

4. HF and/or HTPF are used routinely as part of site characterization of large engineering underground structures, in the design of oil and geothermal fields, and in deep scientific research boreholes.

2. Summary of test methods

5. For both HF and HTPF methods, a section of a borehole is sealed off by use of two inflatable rubber packers sufficiently pressurized so that they adhere to the borehole wall. Hydraulic fluid (typically water) is pumped under constant flow rate into the section, gradually raising the pressure on the borehole wall until a fracture is initiated in the rock, or a pre-existing fracture is mechanically opened. Pumping is stopped, allowing the interval pressure to decay. Several minutes into the shut-off phase, the pressure is released and allowed to return to ambient conditions. The pressure cycle is repeated several times maintaining the same flow rate. Key pressure values used in the computation of the in situ stresses are picked from the pressure–time record. The repeated cycles provide redundant readings of the key pressures. The attitude of the induced HF, or of the pre-existing fracture, is obtained using an oriented impression packer or one of several geophysical logging methods. HF orientation is related to the directions of the principal stresses.

6. With HF, data from the pressurization and fracture orientation phases of the test are used to obtain the in situ principal stresses in the plane perpendicular to the borehole axis. With HTPF, tests yield an evaluation of the normal stress supported by fracture planes with different known orientations, and the complete stress evaluation results from an inversion of these results.

3. Assumptions and limitations

3.1. Hydraulic fracturing (HF)

7. The following points should be noted with respect to HF.

- There is no theoretical limit to the depth of measurement, provided a stable borehole can access the zone of interest and the rock is elastic and brittle.
- Classical interpretation of an HF test is possible only if the borehole axis is parallel to one of the principal stresses and is contained in the induced fracture plane. The initiation of 'en echelon' fractures may indicate that the borehole axis is not along a principal stress. Excessive deviation invalidates the classical method of interpretation of test results.
- Principal stress directions are derived from the fracture delineation on the borehole wall under the assumption that fracture attitude persists away from the hole.
- Evaluation of the maximum principal stress in the plane perpendicular to the borehole axis assumes that the rock mass is linearly elastic, homogeneous, and isotropic. It involves considerations of pore pressure effects, often difficult to ascertain, and requires an assessment of the rock tensile strength.

3.2. Hydraulic tests on pre-existing fractures (HTPF)

8. The following points should be noted with respect to HTPF.

- There is no theoretical limit to the depth of measurement, provided a stable borehole can access the zone of interest.

- The method assumes that isolated pre-existing fractures, or weakness planes, are present in the rock mass, that they are not all aligned within a narrow range of directions and inclinations, and that they can be mechanically opened by hydraulic tests. When the straddled interval includes multiple fractures, it is necessary to verify that only one single fracture has been opened, for the opening of pre-existing fractures change the local stress field.
- Fractures used in stress computations are delineated on the borehole wall under the assumption that their orientation persists away from the hole.
- For a complete stress tensor determination, the method requires a theoretical minimum of six tests, each conducted on pre-existing non-parallel fractures; but additional tests are recommended in order to correct for uncertainties. However, when combined with HF tests, only three–four HTPF results are necessary for the maximum horizontal and vertical stress components determination.
- The method is valid for all borehole orientations. It is independent of pore pressure effects and does not require any material property determination.
- It assumes that the rock mass is homogeneous within the volume of interest. When tested fractures are distant from one another by more than 50 m, a hypothesis on stress gradients is required.

4. Apparatus

The same apparatus is necessary for HF and for HTPF, see Figs. 1 and 2.

9. *Surface equipment*: A sturdy tripod or a drilling rig is placed over the borehole collar for tripping the downhole tools necessary for conducting the tests. When drill pipe or steel tubing is used for lowering the tools, a drilling rig is preferred because it can accommodate the heavy weight of the downhole assembly. A tripod may be used when tools are lowered on the much lighter wireline.

10. *Straddle packer*: Sealing of the borehole test interval is accomplished by use of two inflatable rubber packers, spaced apart a distance equal to at least six times the hole diameter. The two packers are connected mechanically as well as hydraulically to form one unit termed the straddle packer.

11. *High-pressure tubing, drill pipe, or hose*: Generally, rubber packer inflation and test interval pressurization are carried out hydraulically from the surface, although for deep tests often associated with the petroleum industry, equipment exists that employs a pump directly attached to the straddle packer and is remotely controlled. Hydraulic fluid is conveyed downhole typically through the use of high-pressure stainless steel tubing, flexible hose, or drill pipes (also called drill rods). When drill rod is used, it also serves for tripping the hydrofracturing equipment. Tubing or hose require an additional means of lowering and lifting the test tools, such as drill rod or wireline.

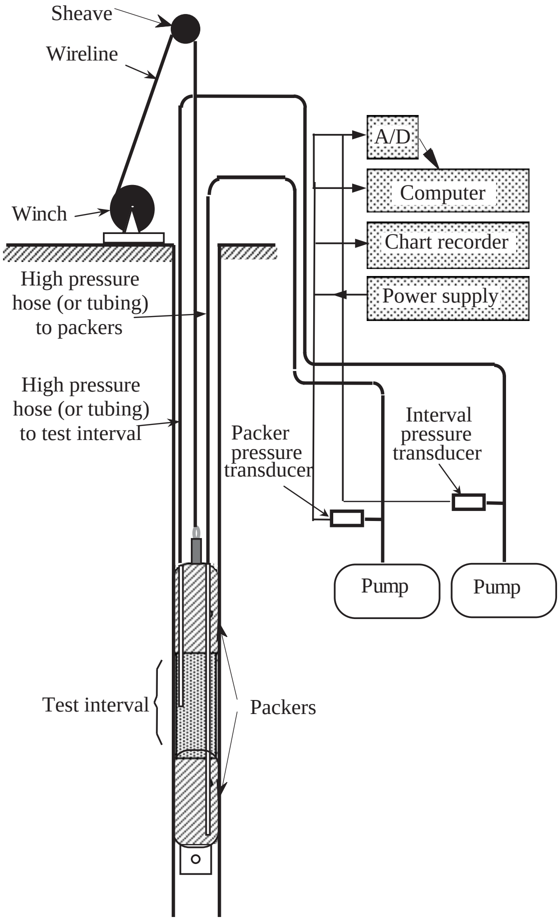

Fig. 1. Typical HF test equipment setup.

12. *Pressure gages, pressure transducers, and flow meter*: Pressure gages are used on the surface to give visual real-time information of the hydraulic fluid pressure. Pressure transducers are used to monitor and transmit pressure data to a recording device. In some setups, only the test interval pressure is monitored. The preferred arrangement is one in which the packers and the interval are pressurized and monitored independently. For shallow tests, surface transducers are sufficiently accurate. For depths exceeding several hundred meters, downhole pressure transducers (or transmitters) emplaced close to the location of the packers are preferred. These provide a more accurate recording of the test interval pressure. A flow meter is employed to monitor the flow of fluid into the test interval. Typically this is a surface device.

13. *Pressure generators*: Most often, hydraulic fluid pressure is provided by a pump or pumps located on the surface. However, for deep tests, equipment exists for which the pump is fixed on the straddle packer. Some

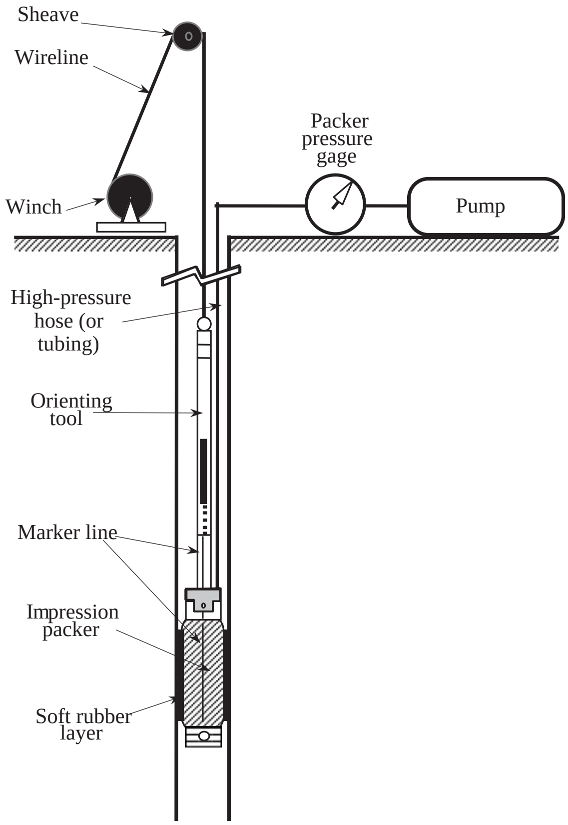

Fig. 2. Typical impression packer test equipment setup.

pumps are capable of providing up to 100 MPa at a typical flow rate range of 1–10 l/min. The pump is powered electrically, pneumatically, or by use of a combustion or diesel engine.

14. *Recording equipment*: Analog data from the pressure transducers and flow meter are fed into a computer data acquisition program via an analog/digital board. Separate analog real-time reading of the test-interval and packer pressures and of the flow rate are often provided by a multi-channel strip-chart recorder.

4.1. Fracture orientation detection devices

15. *Impression packer*: An image of the borehole wall within the test interval is commonly obtained using an impression packer, an inflatable packer with an outer layer of very soft semi-cured rubber. This packer is inflated when it is positioned precisely at the same depth as the HF test interval, resulting in an impression of the borehole wall and any fractures that traverse it.

16. *Orienting tool*: Attached to the impression packer is an orienting tool, which can be magnetic or gyroscopic. The magnetic tool enables a camera to photograph the position of magnetic north on the borehole wall, from which the orientation of any induced fractures can be obtained. It is considerably easier and less expensive to use than a gyroscopic tool, but is of little use in magnetic rocks (such as basalt, some gneiss, and others). Geophysical tools, such as borehole cameras, borehole televiewers (a sonic device) or electrical imaging systems are also available for fracture orientation determination.

17. All these fracture orientation techniques have their own advantages and limitations. However, when the electrical imaging system is directly mounted on the straddle packer, the same tool provides initial borehole reconnaissance (no need for cores), exact positioning at selected depth intervals, real-time imaging of fracture opening, and combined electrical and hydraulic signature of fracture opening and closing.

5. Personnel qualification

18. *Drilling personnel*: Quality drilling is essential for obtaining good core, circular cross-sections, and nearly vertical boreholes. This requires experienced drillers. They are also needed for tripping equipment downhole and for operating the drill rig when tool jamming occurs.

19. *Test personnel*: Test performance may vary from one location to the other, and from one rock type to the next. Field testing often requires quick decisions that may affect the success of the measurement campaign. Hence, the test personnel should be well versed with the theoretical aspects of the method, and should have considerable experience with such tests in a variety of rock types, depths, and locations.

6. Equipment performance

20. Quality control is an integral part of a successful test. Transducers, gages, flow meters, magnetic compass, and recording equipment should be calibrated prior to a stress measurement campaign. Equipment and apparatus should be verified for compliance with performance specifications. For depths greater than a few hundred meters, when depth measurements involve both drill pipe and wireline systems, their equivalence should be explicitly demonstrated by comparing measurements at unambiguous reference points. This is of particular importance for properly matching core lengths, geophysical imaging logs, test interval depths and images or prints of tested intervals.

7. Hydraulic fracturing test procedure

During any test, continuously record the test interval and straddle packer pressures, the instantaneous injection flow rate and the total injected volume. When possible, keep track of the various vented volumes.

The following procedure is illustrated by Figs. 1, 3 and 4.

21. Drill borehole (generally the vertical direction is recommended in the absence of topographical or structural effects), and extract continuous core or obtain clear and oriented borehole images. Depending on project and rock type, typical borehole diameters range from 76 to 96 mm (N- to H-size) in site investigations for underground civil structures, and may extend to 180 mm in deep petroleum, geothermal or scientific wellbores. Core or borehole images are essential for selecting intact test intervals and for identifying the rock formations to be tested. Cores are also necessary for any additional laboratory tests that may be useful for complementing the field tests. However, for deep boreholes, preference is given to rotary drilling associated with geophysical imaging as a less expensive alternative to diamond drilling and coring.

22. For HF, select test zones that are devoid of fractures or other disturbances and are at the appropriate depths as per project requirements. For HTPF, select well-isolated planar fractures with dip and azimuth sufficiently variable to sample properly the state of stress. Extracted core and geophysical logs (such as caliper, sonic, density, televiewer or electrical imaging) are all useful for this purpose.

23. Seal off the test interval by positioning the straddle packer at the planned depth, and pressurize the packers to a typical level of 2–4 MPa. Such pressure will anchor the packers to the borehole wall without creating any fracturing (unless the rock is unusually weak). The hydraulic fluid is generally water, although alcohol may be preferred in some instances.

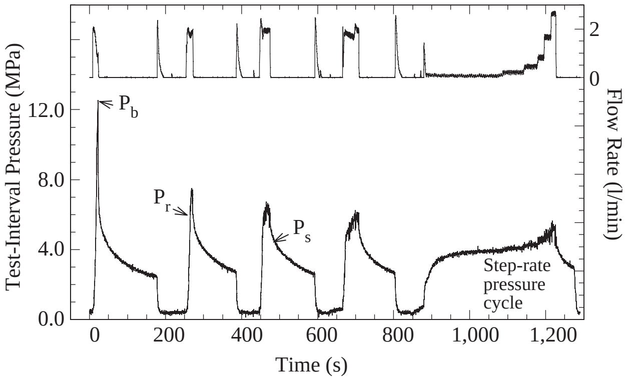

Fig. 3. An actual record of test-interval pressure and flow rate versus time. The precise magnitudes of P_r and P_s are determined using techniques listed in this SM.

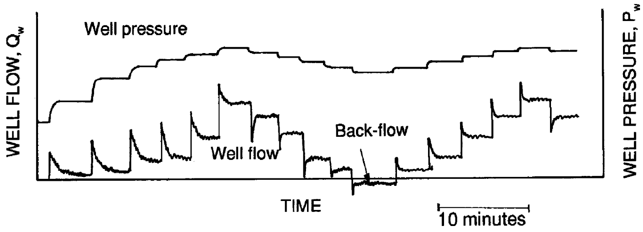

Fig. 4. A typical step cycling pressure test. The pressure is first raised, then decreased, in a stepwise manner, each step lasting 4–5 min [9].

24. Pressurize the test interval for an initial qualitative permeability inspection (slug test). A downhole valve is preferred for a more accurate relation between the pressure decay and the local rock permeability.

25. Raise the interval pressure maintaining a constant, predetermined, flow rate. Note that the flow rate may depend on rock permeability and that the aim is to raise the interval pressure steadily so that the peak pressure at which rock at the borehole wall fractures (termed breakdown pressure), or the pre-existing fracture opens, is reached in 1–3 min. The hydraulic fluid may be adjusted to the local material characteristics, in particular in clayish or salty environments. With surface pumps, the fracturing fluid is conveyed to the test interval through a separate string of tubing or hose. In some cases, one single string for both packer inflation and test interval is used, and the destination is controlled by a downhole valve. Throughout pressurization, the packer pressure is maintained at about 2 MPa higher than the interval pressure to ensure isolation. This can be best monitored and controlled if separate hydraulic lines and pumps are used.

26. Upon reaching breakdown pressure (or fracture opening), stop pumping but do not vent. Interval pressure will decay, first at a fast pace while the HF is still open and growing, and then at a much slower pace, after the fracture has closed. The pressure at which the fracture closes is termed shut-in pressure. A few minutes (typically 3–10 min) after shut-in the hydraulic line is vented.

27. An optional step here is that after venting a small volume (typically half a liter), the test interval is closed back and the rise in pressure is monitored. When the initial permeability test has shown that the rock is fairly impervious, this operation provides a means to verify that the fluid has been injected into the rock mass and that no significant bypassing to the borehole has occurred. However, in very porous and permeable environments, no rise in pressure may be observed. In such cases, it may be advisable to verify that injected flow rates are large enough to open the tested fracture for long enough distances. Finally, depending on test objectives, pressure is allowed either to reach ambient level if the step in Paragraph 28 is to be undertaken (which may take from a few seconds up to 30 min depending on site conditions), or the step in Paragraph 29 and/or Paragraph 30 is conducted immediately.

28. *Fracture reopening—option 1* (*for HF method only*): After the pore pressure has reached its original value, i.e. after waiting for a few minutes, repeat the above pressurization cycle at least three times, using the same flow rate. The flow rate should be sufficiently high

to prevent fracturing fluid percolation into the closed fracture before the actual mechanical fracture opening. The additional cycles yield additional shut-in pressure values as the fracture is extended by the additional pumping. The peak pressures are discernibly lower than in the first pressure cycle, because the reopening of the fracture does not require overcoming the tensile strength of the rock. This yields the fracture reopening pressure. The fracture reopening pressurization cycles are recommended only for the HF method. They should not be undertaken with the HTPF method in order to limit chances of creating a real HF when a pre-existing fracture is being tested.

29. *Fracture reopening—option 2* (*for HTPF and HF methods*): After the step in Paragraph 28 for HF, or directly after the venting and flow back of the step in Paragraph 27 for HTPF, conduct a step-rate pressurization cycle, in which the flow rate is first brought to a very low level and maintained constant while the pressure increases until it reaches a plateau. Thereafter, the flow rate is raised to a new step and again the pressure is allowed to equilibrate at a constant level, and this is repeated several times, yielding an array of constant pressure levels obtained at different flow rates. Typically, each constant pressure step lasts about 5 min. Once the fracture is fully open, injection stops and the test interval is sealed off for pressure drop monitoring. This provides an additional shut-in pressure reading. With the HTPF method, this cycle is conducted at least twice but possibly more, so that, combined with the step in Paragraph 26, a minimum of three shut-in pressure readings is produced.

30. *Fracture reopening—option 3* (*for HTPF and HF methods*): This option is similar to option 2, except that, after reaching the maximum injection flow rate, the pressure is decreased progressively in a stepwise manner, so as to reach complete closure of the fracture. This closing process is taken to advantage for an additional independent shut-in pressure determination. It complements efficiently the step in Paragraph 29.

31. At the conclusion of the test, vent not only the test interval but also the packer pressure, to allow the packers to deflate so that they can be moved to the next testing depth.

32. Repeat the entire test, as described in Paragraphs 21–31, at all selected depth intervals.

8. Hydraulic-fracture delineation

The text here is illustrated by Figs. 2 and 5.

8.1. Impression packer technique

33. When using the oriented impression packer to delineate the induced fracture on the borehole wall, trip the packer to the depth where its center coincides with that of the HF test interval. Inflate the impression packer to a pressure just higher than the recorded shut-in level and maintain it there for about 30 min. This enables a slight opening of the fracture, allowing the penetration of the soft rubber enveloping the impression packer. The amount of time is calculated to ensure that the fracture imprint on the packer will be preserved permanently.

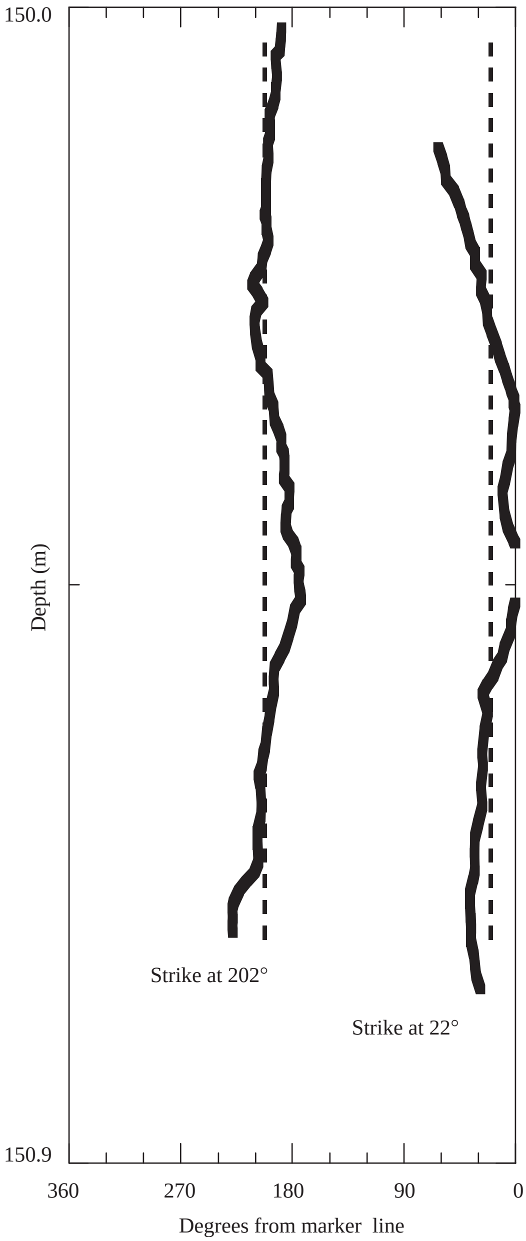

Fig. 5. An actual impression packer test record showing the HF trace on the borehole wall (thick lines), and the mean vertical plane occupied by the fracture (dashed lines).

34. During the inflation period, a camera mounted in the orienting tool attached to the impression packer is triggered by a preset clock to take a photograph of the face of the tool's magnetic compass, and of a

line aligned with a marker on the packer. Thus, the impression packer is oriented with respect to magnetic north, enabling the orientation of any logged fracture.

35. Upon the retrieval of the impression packer, the camera film is developed, and the image of the compass face, showing the direction of the packer marker with respect to magnetic north, becomes part of the test record. The imprints of the HF on the impression packer are traced relative to the oriented marker on a wrapped-around transparent plastic sheet. The traces can be digitized to facilitate statistical evaluation of the average strike and dip of the induced fractures.

8.2. Geophysical imaging technique

36. Various geophysical techniques are available for fracture imaging. Comparison between cores, acoustic and electrical imaging [4] shows that, when fractures are closed, the thinnest ones are missed on geophysical imaging logs. However, in deep strongly deviated boreholes, the use of impression packers is not recommended. Further, it is not clear whether fractures observed on cores are significant in situ [5]. In addition, in many instances, a test zone may exhibit multiple fractures. Thus, geophysical techniques have been developed for identifying the one fracture that has been tested hydraulically, when multiple fractures are observed.

37. Electrical imaging techniques have proven efficient for mapping hydraulically opened fractures in all rock types except claystone and salt, because of their electrical properties. However, recent developments suggest that satisfactory images may be obtained in these rocks, by adapting the salinity of the fracturing fluid to that of the rock environment.

38. The choice of the proper tool for fracture mapping depends largely on the local availability of corresponding tools. Generally, impression packers are more frequently used in shallow (several hundred meters), small diameter (from 76 to 120 mm) reconnaissance boreholes for the design of civil structures, while geophysical techniques are more favored at greater depths. However, while impression packers have been used successfully at fairly large depths (over 1500 m), geophysical imaging has proven cost-competitive in shallow environments.

9. Obtaining critical pressure parameters from the pressure–time records

39. The breakdown pressure (P_b) is taken as the peak pressure attained in the first pressure cycle. It is the pressure required to induce a hydraulic fracture in HF tests, or fracture opening in HTPF tests. After reaching its peak, pressure typically declines even if pumping is continued at the initial flow rate.

40. The fracture reopening pressure (P_r) is the point on the ascending portion of the pressure–time curve in subsequent (usually second or/and third) cycles described in the step in Paragraph 28 (option 1 of reopening cycle), where the slope begins to decline from that maintained in the first (breakdown) cycle. The slope decline, while maintaining constant flow rate, signifies that some fluid has infiltrated the reopened fracture. A method for objectively defining P_r is detailed in [7].

41. The shut-in pressure (P_s) is the pressure reached, after the pump is shut off following breakdown or fracture reopening, when the hydraulically induced or the pre-existing fracture closes back. Various methods are in use for evaluating this pressure (see Paragraphs 42–44).

42. The first set of methods are based on the analysis of pressure decay just after shut off. An upper bound to the shut-in pressure is provided by the determination of the pressure when the process of fracture mechanical opening stops, while a lower bound is provided by the pressure for which the fracture has completely closed back. Hayashi and Haimson [6] propose to determine the end of fracture opening from a regression analysis of the plot of $\mathrm{d}t/\mathrm{d}P$ versus P, where P is pressure and t is time. A straight line is fitted to the first portion of the $\mathrm{d}t/\mathrm{d}P$ versus P data. The point of departure of the remainder of the curve from the straight line is taken as P_s. Identification of the pressure for which the fracture has completely closed is obtained from the analysis of the final portion of the pressure decay curve, when flow obeys a law similar to the Darcy Law. The shut-in pressure may also be derived from the rate of pressure decay ($\mathrm{d}P/\mathrm{d}t$) as a function of pressure [7] or from the plot of $\log(P)$ versus time [8]. In both cases, the lower bound of P_s is provided by the highest pressure value for which the linear regression analysis is valid.

43. A different method involves the results of the step pressurization and depressurization cycles (the steps in Paragraphs 29–30, reopening options 2 or 3). Plotting pressure as a function of flow rate for either the increasing or the decreasing pressure sequence of the step in Paragraph 30, i.e. the fracture opening or closing phase, one obtains a bilinear curve the point of intersection of which is taken as the shut-in pressure P_s [7,9]. Whether the fracture opening or the fracture closing phases are used for assessing P_s, utmost care must be taken in interpreting the steprate pressurization cycle to prevent erroneous results [9,10].

44. It is strongly recommended that more than one method be used for obtaining the crucial P_s parameter. Typically, at least two independent methods are employed for the same test to ensure reliability of the shut-in pressure value. If values do not coincide, a thorough study of the testing procedure and rock type should reveal the more reliable magnitude.

10. Stress calculations

10.1. Hydraulic fracturing (HF)

45. The calculations of in situ principal stresses given hereafter are for vertical boreholes (commonly used for HF), and for tests yielding vertical fractures (both within ±15° or so). This corresponds to the case in which the vertical stress component acts along a principal direction.

46. *Least horizontal principal stress magnitude and direction (*σ_h*).*

Vertical HFs are oriented perpendicular to the direction of the minimum horizontal principal stress. The shut-in pressure (P_s) is the pressure needed to equilibrate the fracture-normal stress, which in this case is σ_h

$$\sigma_h = P_s. \tag{1a}$$

The direction of σ_h is obtained directly from the azimuth of the HF:

$$\sigma_h \text{ direction} = \text{direction of normal to vertical hydraulic fracture.} \tag{1b}$$

47. *Largest horizontal principal stress direction and magnitude (*σ_H*).*

This principal stress is calculated based on the assumption of linear elasticity and insignificant effect of fracturing fluid rock infiltration: In the absence of pore fluid in the rock mass, the maximum horizontal principal stress magnitude is given by Eq. (2a)

$$\sigma_H = T + 3\sigma_h - P_b, \tag{2a}$$

where T is the tensile strength of the tested rock, and P_b is the breakdown pressure.

48. In saturated rocks with low permeability, so that there is no percolation of the fracturing fluid in the formation before fracture opening, it is often assumed that pore pressure is unaffected by the state of stress and that Terzaghi's effective stress concept applies to tensile ruptures. In this case Eq. (2b) is employed:

$$\sigma_H - P_o = T + 3(\sigma_h - P_o) - (P_b - P_o). \tag{2b}$$

More elaborate pore pressure corrections have been proposed, e.g. [11,12]. They outline the necessity to better understand coupling effects and its dependency on the local stress state.

49. The maximum horizontal principal stress is perpendicular to the σ_h direction:

$$\sigma_H \text{ direction} = \text{direction of vertical hydraulic fracture strike.} \tag{2c}$$

50. Whatever the role of pore pressure, solving Eqs. (2a) or (2b) requires that the rock tensile strength be known The tensile strength can only be directly measured in the laboratory on core samples. The most common tensile test is the Brazilian test, which enables the testing of many disks cut directly from the extracted core. The Brazilian test configuration, however, does not simulate conditions under HF, and the reliability of this test as representative of the tensile strength for HF has not been established. Core is also used to prepare hollow cylinders, which are fractured by applying internal pressure, with no external confining stress. This test accurately simulates an HF test in which there are no far-field stresses, and therefore the peak pressure is equal to the tensile strength T. The only unknown in such tests is the scale effect between field and laboratory dimensions.

51. When extracted core is not available, or laboratory tests are not feasible, or when tension tests appear to yield an unreasonable value for use in Eqs. (2a) or (2b), an alternative relation has been used, invoking the fracture reopening pressure (P_r). This pressure is assumed to be that at which the induced fracture, which has closed completely after initial pressure cycle, reopens. This time, however, fracture reopening does not have to overcome the tensile strength T, and thus Eq. (2b) becomes

$$\sigma_H - P_o = 3(\sigma_h - P_o) - (P_r - P_o). \tag{3}$$

This equation for calculating σ_H has been widely used in field measurement campaigns. There is, however, considerable controversy regarding its reliability in cases such as when:

- the induced fracture has not completely closed after each pressure cycle or the pore pressure has not returned to its original value [3,13],
- P_r has not been identified objectively on the pressure–time record [7],
- the volume of fluid pumped into the test interval is so large as compared to the intake of a slightly opened fracture that the correct P_r on the pressure–time curve may be missed [14].

52. This is where the qualification and experience of the test personnel is particularly important in order to ascertain whether the picked value of the fracture reopening is a correct one. Hence, because of difficulties with both pore pressure effects and tensile strength estimation, the evaluation of the maximum horizontal principal stress magnitude involves a greater uncertainty than that of the minimum horizontal principal stress magnitude.

53. *Vertical stress* (σ_v): This component cannot be evaluated from test results unless the induced fracture is nearly horizontal, in which case the recorded shut-in pressure is taken as equal to the vertical stress σ_v. Otherwise, σ_v is assumed to be equal to the overburden weight per unit area at the depth of interest:

$$\sigma_v = \sum_{i=1}^{n} \rho_i g D_i, \tag{4}$$

where ρ_{I} is the mean mass density of rock layer I; g is the local gravitational acceleration; D_{I} is the thickness of layer I; and n is the number of rock layers overlying the test zone.

10.2. Hydraulic tests on pre-existing fractures

54. With the HTPF method, the stress tensor is evaluated so as to best fit the normal stress measurements obtained for all the tested fractures. This requires a parameterization of the stress field and the definition of a misfit function.

55. *Parameterization of the stress field*: It takes six parameters to characterize the complete stress tensor at any given point. Hence a complete stress determination requires theoretically a minimum of six different tests on fractures with different dip and azimuth in order to solve the linear system provided by[1]

$$\sigma_n^m = \boldsymbol{\sigma}(\mathbf{X}_m)\mathbf{n}_m\mathbf{n}_m, \tag{5}$$

where $\mathbf{X}_m$ is the location of the mth test, σ_n^m is the measured normal stress supported by the fracture plane with normal $\mathbf{n}_m$ and $\boldsymbol{\sigma}(X_m)$ is the stress tensor at $\mathbf{X}_m$. m varies from 1–N, for a total of N complete HTPF measurements (normal stress and fracture plane orientation determination).

56. However, because measurements are never exact and always encompass some uncertainty, it is always desirable to conduct more tests than there are unknowns. If a complete stress tensor determination is required, a minimum of eight tests are necessary. When less than eight tests are available, efforts are undertaken to decrease the number of unknown for the stress tensor. For example, in some instances, it may be assumed that the vertical direction is principal (this leaves only four unknowns) and that the vertical component is equal to the weight of overburden (this leaves only three unknowns). In the latter case, only five HTPF measurements will be necessary for the stress determination, but the vertical component will not be determined directly from the HTPF results.

57. It may also happen that the distances between the various tests are so large that stress gradients must be considered. Then, the number of unknowns increase and so does the minimum number of tests required for a satisfactory determination. It has found to be convenient to parameterize the stress field by assuming a linear variation along the borehole axis in which measurements are conducted:

$$\boldsymbol{\sigma}(\mathbf{X}_m) = \boldsymbol{\sigma}(\mathbf{X}_0) + (\mathbf{X}_m - \mathbf{X}_0)\boldsymbol{\alpha}, \tag{6}$$

where the stress at point $\mathbf{X}_m$ may be expressed as a linear function of the stress at point $\mathbf{X}_0$ and $\boldsymbol{\alpha}$ is the stress gradient along the borehole axis.

58. Generally, Eq. (6) involves 12 parameters and requires a minimum of 14–15 tests for its solution. But when the borehole used for the measurements is vertical and there is no lateral stress variation, then the vertical stress gradient is along a vertical principal direction [15] and Eq. (6) involves only 10 unknowns which may be further reduced, possibly to five, depending on simplifying assumptions.

59. *Definition of the misfit function*: The misfit function defines the discrepancy between observed and computed values as determined with a possible stress model. The solution is defined as the stress model which minimizes the misfit function, i.e. the model which is the closest to all the measurements. The misfit must include both errors in normal stress determination and in fracture orientation determination. Various misfit functions have been proposed in the literature. A more complete discussion is offered in [3].

60. *Integration with* HF: While the HTPF method may be used completely independent of the HF method, it has been found convenient to combine both methods when the borehole is parallel to a principal stress direction (generally, the vertical direction). Indeed, in such cases, the HF method yields accurate determination of the minimum principal stress direction and magnitude, while the HTPF results help constrain the magnitudes of the maximum horizontal principal stress and the vertical stress components, without any consideration of either pore pressure or tensile strength. In such instances, only two unknowns exist in Eq. (5), so that only three or four tests on pre-existing fractures are needed to complement the HF tests (a minimum of three is required for redundancy considerations).

11. Reporting of results

The following are the minimum requirements for a complete and usable report.

61. *Introduction*

- purpose of the tests;
- details of site location, including a topographic and location map;
- regional and site geological description (with maps, if available), and the tectonic setting;
- geological log of the test borehole, including the types of rock and the geologic structures encountered;
- reasons for selecting the test-site location as they pertain to the purpose of the tests;
- diameter and length (complete profile for deep boreholes) of the test borehole;
- for deep boreholes (larger than 500 m) demonstration of depth determinations accuracy for the various

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[1] See Part 1 of the ISRM SMs on rock stress estimation for an explanation of stress and the notation used here.

sources of information (cores, geophysical logs, test interval depths, images or prints of tested intervals);
- selected number and depths of individual tests.

62. *Test method*

- Detailed description of the equipment and its setup, including diagrams, specifications and the latest calibration;
- Test procedure, including number and duration of pressure cycles, fluid volume per cycle;
- Explanation of any deviation from the test procedure recommended by this SM.

63. *Theoretical background*

- List of all equations used to derive the state of stress from the HF tests, or description of method used for inverting normal stress measurements produced with the HTPF method;
- Comments should be included on the assumptions inherent in the theoretical relations and their suitability for the conditions in the test borehole;
- In case of disparity between assumptions and local conditions, an explanation is required of what corrections were made, if any, to account for them;
- Method for evaluating the results, uncertainty should be specified.

64. *Test results*: These should include:

- Graphical representations of the complete test-interval pressure versus time, and flow rate versus time for each test;
- Images of the HF traces on the impression packer showing their correct azimuth;
- Graphical representations of the different techniques used to extract correct magnitudes of fracture reopening pressures and shut-in pressures from the pressure–time records;
- Tabulated values of the pore, breakdown, shut-in, and fracture reopening pressures for each test;
- Tabulated strike and dip of hydraulic or pre-existing fracture for every test conducted;
- A separate table containing the computed three principal stresses and their directions;
- When relevant, a graphical representation of each of the principal stress magnitudes as a function of depth, and of the principal stress directions as a function of depth.

65. *Discussion of results*

- Discussion of uncertainties related to the critical pressure determinations, the fracture orientations and the resulting stress evaluation;
- Discussion of the role of heterogeneity and discontinuity on the dispersion of the results, if any;
- Discussion of the validity of the various hypothesis and assumption as postulated a priori (such as: has the vertical direction been proven to be principal? What is the role of topography or of local structures?);
- If suitable, discussion of regional significance of results.

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