P-04-310

Oskarshamn site investigation

Hydraulic fracturing and HTPF rock stress measurements in borehole KSH01A

Ulf Lindfors, SwedPower AB

December 2007

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

ISSN 1651-4416
SKB P-04-310

Oskarshamn site investigation

Hydraulic fracturing and HTPF rock stress measurements in borehole KSH01A

Ulf Lindfors, SwedPower AB

December 2007

Keywords: Stress measurement, Hydraulic fracturing, HTPF, Stress state.

Summary

Hydraulic fracturing (HF) and Hydraulic tests on pre-existing fractures (HTPF) stress measurements were conducted in borehole KSH01A at the Oskarshamn site. The equipment used for the measurements was SwedPower´s mobile unit for hydraulic stress measurements with a 1,000 m long multihose.

Hydraulic fracturing tests were attempted at three main measurement levels in borehole KSH01A. The first measurement level included fracturing tests at 179 m borehole length. Fracturing tests at the second level were carried out between 510 and 530 m borehole length. The third level comprised a fracturing test at 707 m borehole lengths.

A number of HTPF tests were conducted along the borehole between 380 and 745 m borehole length. In according to each HTPF test, a fracturing reopening was conducted, also called "jacking test". These jacking tests were extended to include both stepwise increasing and decreasing step-rate pressurization cycles.

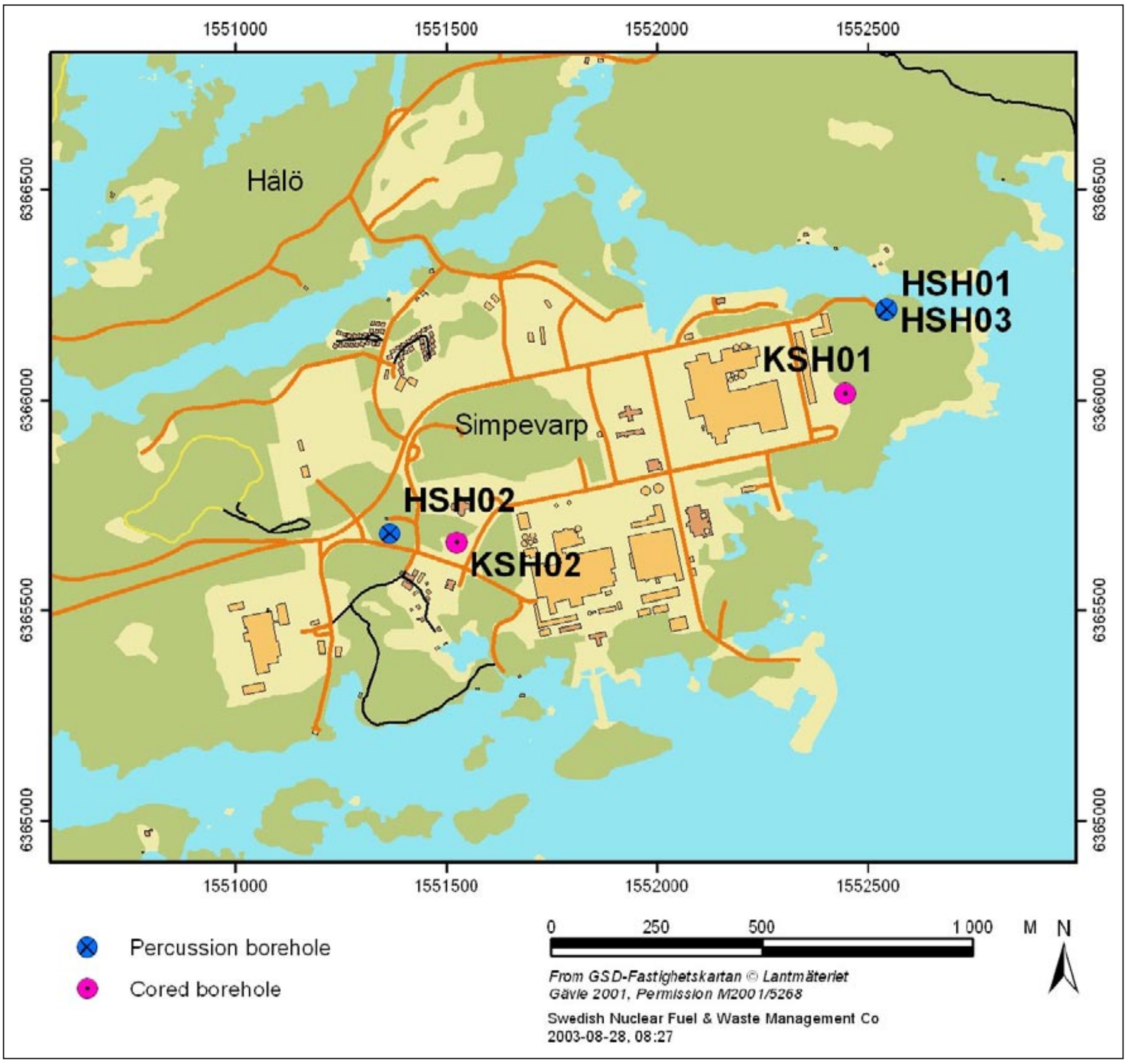
The magnitudes of the horizontal stresses are moderately high. The maximum horizontal stress is in the range of 20–30 MPa (at 500 m depth), and the minimum horizontal stress is 10–12 MPa (at 500 m depth). The orientation of the maximum horizontal stress is E-W to ESE-WNW.

Contents

1 Introduction

This document reports the data gained from Hydraulic fracturing (HF) and Hydraulic tests on pre-existing fractures (HTPF) stress measurements conducted in borehole KSH01A, which is one of the activities within the site investigation at Oskarshamn. The location of the hole, in relation to other investigation boreholes in the area, is shown in Figure 1-1.

The borehole was drilled subvertically (at approximately 75° dip) from the ground surface and is of "telescope" type with the upper 100 meters of larger diameter (250 mm), which subsequently is cased. The rest of the borehole is drilled with 76 mm diameter down to a length of 1,000 meters. Hydraulic fracturing and HTPF rock stress measurements were planned to be conducted between borehole length 179 m and 744 m, according to the activity plan AP PS 400-04-015 (SKB internal controlling document).



From GSD-Fastighetskartan © Lantmäteriet Gävle 2001, Permission M2001/5268

Swedish Nuclear Fuel & Waste Management Co 2003-08-28, 08:27

***Figure 1-1.** Location of core holes (initial "K") and percussion-drilled (initial "H") holes within the Oskarshamn candidate area.*

The dominating rock types in the area are dioritoid and granite, and the dominating rock domains determined for the area includes Ävrö granite and a mixture of Ävrö granite and quartz monzodiorite /SKB 2004/.

Comparing the geology in the borehole /Ask et al. 2003/ and determined measuring levels, tests performed above 200 m borehole length are conducted in Quartz monzodiorite, tests performed between 380 and 540 m borehole lengths are conducted in Fine-grained dioritoid, tests performed between 650 and 680 m borehole lengths are conducted in Ävrö granite and Granite and tests performed below 680 m borehole length are conducted in Quartz monzodiorite. In the borehole, the majority of open fractures strikes E-NE to W-SW /SKB 2004/.

2 Objective and scope

The objective of the hydraulic fracturing and HTPF rock stress measurements was to determine the horizontal in situ stress field in the undisturbed rock mass. One principal stress direction was assumed aligned with the vertical direction (the vertical stress) and assumed to correspond to the weight of the overlying rock mass. To achieve the objective, six (6) hydraulic fracturing tests and nineteen (19) HTPF tests were performed along the borehole. In additional, an intention of the HTPF tests on sub-horizontal fractures was to compare the normal stress acting on these fractures with the theoretical load of the overburden rock.

All measurements were conducted using the hydraulic fracturing equipment owned by SwedPower AB. The method is described in detail in Chapter 3 of this report. Field measurements started February 23 and were completed March 17, 2004.

Execution of field measurements and data analysis is presented in Chapter 4 of this report and results are described in Chapter 5. Measurement and analysis data from the tests are reported in Appendices A through D.

The presentation of this report is restricted to the fieldwork and analysis of the collected data. No attempts to put the data into a geological/tectonic context, or to discuss the implications of the results for future work.

3 Equipment

3.1 Description of field equipment

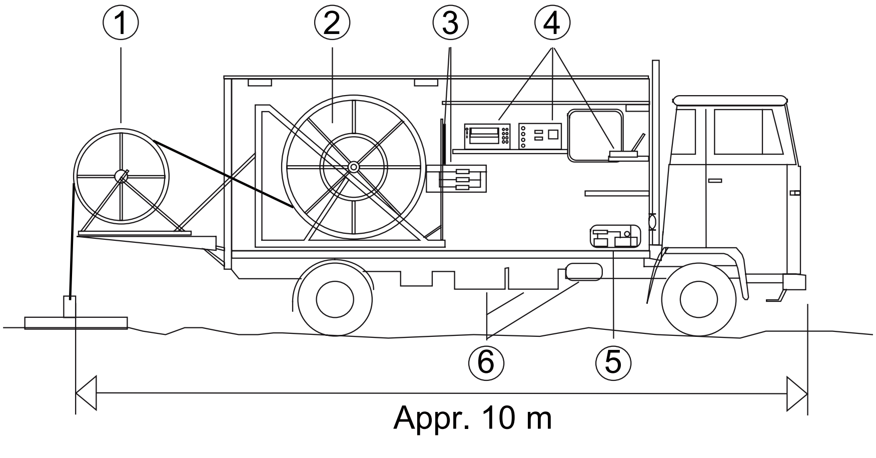
The hydraulic fracturing equipment is owned and used by SwedPower AB for stress measurements in 56 and 76 mm boreholes. The entire instrumentation is permanently installed on a field truck, and measurement operations are controlled from inside the truck cabin. Electricity is the only external power source needed. The truck engine powers all other functions of the system. The main components of the system are illustrated and listed in Figure 3-1.

During actual measurements, a section, normally less than 1 m in length, of a borehole is sealed off with a straddle packer. In this work the test section is reduced to 0.5 m length. The sealed-off section is then slowly pressurised with water. This generates tensile stresses at the borehole wall. Pressurisation continues until the borehole wall ruptures through tensile failure and a hydro-fracture is initiated. Both the straddle and the imprint packer are suitable for 76 mm boreholes, the packers also have a steel cord to avoid damages when applying high pressures. Packers are inflated with water and the pump used for the tests has a maximum pumping capacity of 100 MPa. For normal working conditions, as in this project, maximum capacity is reduced to 45 MPa with a safety regulator.

In this project the following gauges were used:

- pressure gauge used for packer pressure, range 0–60 MPa,
- flow gauges used for water flow, pumped into test section, range 0–20 l/min,
- pressure gauge for water pressure, placed in the test section, range 0–50 MPa, and
- pressure gauge for water pressure, placed at surface, range 0–60 MPa.

Data is recorded both in digital form using a computerized data acquisition system and, as back up, in analog form through a time-based chart recorder. All raw data signals sent from the gauges are transferred through an A/D converter.



1 Guide wheel for multihose on adjustable working platform.
2 Drum for 1,000 m multihose.
3 Flow meter manifold and manifold for control of fracturing flow and packer pressure.
4 Data registration equipment, signal amplifier, chart recorder and portable PC.
5 High-pressure water pump.
6 400 l diesel fuel tanks, hydraulic pump and -tank.

Figure 3-1. *The truck-mounted hydraulic fracturing unit used both for the hydraulic fracturing and the hydraulic tests on pre-existing fracture measurements.*

4 Execution

4.1 Preparations

Preparations before measurement start include a control and test procedure of the following details of the equipment:

- Electrical system in the truck.
- Water line system (incoming water, multi-hose and packer systems).
- Low-pressure pump.
- High-pressure pump.
- Amplifier.
- Strip chart recorder (plotter).
- Computer.
- Inflation and the imprint packers using steel-tubes and manometer.

4.2 Execution of measurements

Rock stress measurements by the HF and HTPF method are following the main standard procedure, conducted in the following sequence:

1. Calibration of multihose length (both HF and HTPF).
2. Determination of the position of tests in the borehole from the core logging results (both HF and HTPF).
3. Lowering the straddle packer into the borehole to the measurement depth and inflation of packers (both HF and HTPF).
4. Pressurisation of the fracturing section (both HF and HTPF).
5. Determination the fracture orientation by using an impression packers and a single shot camera unit with a magnetic compass (both HF and HTPF).
6. Determination of tensile strength of the rock mass at position for each HF test.

How each above mentioned step is conducted in this work is described in more detail in the sections below.

4.2.1 Calibration of multihose in the borehole

From the beginning of the project it was intended that a calibration of the multihose were to be conducted against the reference grooves made in the borehole (SKB MD 620.010e SKB, internal controlling document). For calibration, a detector, supplied by the Client, was supposed to be adapted to the measuring equipment. When the hose was calibrated referring to the references grooves, the right position along the hose for each test was, during this work, to be kept by using a 50 m measuring tape.

During mobilisation at site, the hydrofracturing equipment and the detector were adapted to each other. Also a “dummy”, to be used as a substitute for the detector, was made at the initial part of the work for calibration of the multihose. This “dummy” was replacing the detector as the accessibility along the borehole with all equipment (both packers, borehole cameras and detector) was tested. The use of a "dummy" was to avoid damages to the detector. Initially, the complete system including the "dummy" had difficulties passing some parts of the borehole, but the client gave clearance to start up the calibrations of the borehole using the detector.

The calibration was successful at the shallow part of the borehole but below 240 m borehole length, the signal from detector disappeared and the system could not be used for further calibration. Although, since the calibration of the upper part (above 240 m) was successful and showed consistency between detector and measuring tape, it was determined by the client to continue the tests, with positioning based on 50 m measuring tape. A "control" of positioning was supposed to be done with the knowledge of existing fractures and imprints of them. According to this decision, two imprints were made after the HTPF tests, at 380.57 m and 706.51 m borehole length.

4.2.2 Selection of position for HF and HTPF tests

For a hydraulic fracturing test a fracture free section more than 0.5 m in length is required. The core logging results are used to determine the exact position of the each test. In this project, a roughly determined position for each test was given by the Client and a final, more detailed determination was performed by the SwedPower field crew. The final decisions regarding the positions of HF test were made after closer investigation of the rock cores from areas of the chosen depths.

For a HTPF test, the exact location of the fracture must be determined so there are no uncertainties that:

- it is one single fracture tested at each location, and
- the orientation of tested fractures is well defined (planar).

In this project, the number and the orientation of the pre-existing fractures for HTPF testing were provided by the Client. The selection of suitable fractures and their orientation were taken from the results of core logging, RAMAC and BIPS logging of the borehole /Aaltonen et al. 2003/. The validity of the data for pre-existing fractures is referred to the results from core logging done by the client and internal document for the RAMAC and BIPS logging of the borehole. Thus, fracture orientations were only based on previous data, no imprint tests were conducted to verify these (per specification by the client).

4.2.3 Positioning of the packers

With the knowledge of the positions for the tests, the straddle packer was lowered down in the borehole and placed in position by using the calibration of the multihose. When the straddle packer were in the exact position for the tests (HF or HTPF), it was inflated, however it was inflated to a lower pressure than the anticipated fracturing or re-opening pressure (to avoid creating new fractures or opening of existing fractures).

4.2.4 Pressurisation of the fracturing section

HF procedures in this project were performed according to the method description (SKB MD 182.003e, internal controlling document), as follows:

- Pressurisation of the sealed off section is conducted at a constant flow rate, about 3.5 l/min, resulting in breakdown within approximately 30 seconds. The test line is shut-off immediately after breakdown is recorded, but not drained. The shut-in curve is normally recorded 3–4 minutes after shut-off and after that the test section is drained, see Figure 4-1 and Figure 4-2.

- The first pressurisation cycle is followed by three cycles where pressurisation is conducted at the same constant flow rate (3.5 l/min). However, the pumping time after reopening of the fracture is extended for each cycle in order to cause a stepwise propagation of the fracture out from the borehole wall and to record the subsequent change in shut-in pressure as a function of fracture extension or geometry. Each pressurisation cycle is followed by draining of the test section. During the whole test period the packer pressure is maintained at about 2–4 MPa above the pressure in the sealed of section to ensure that no leakage occurs.

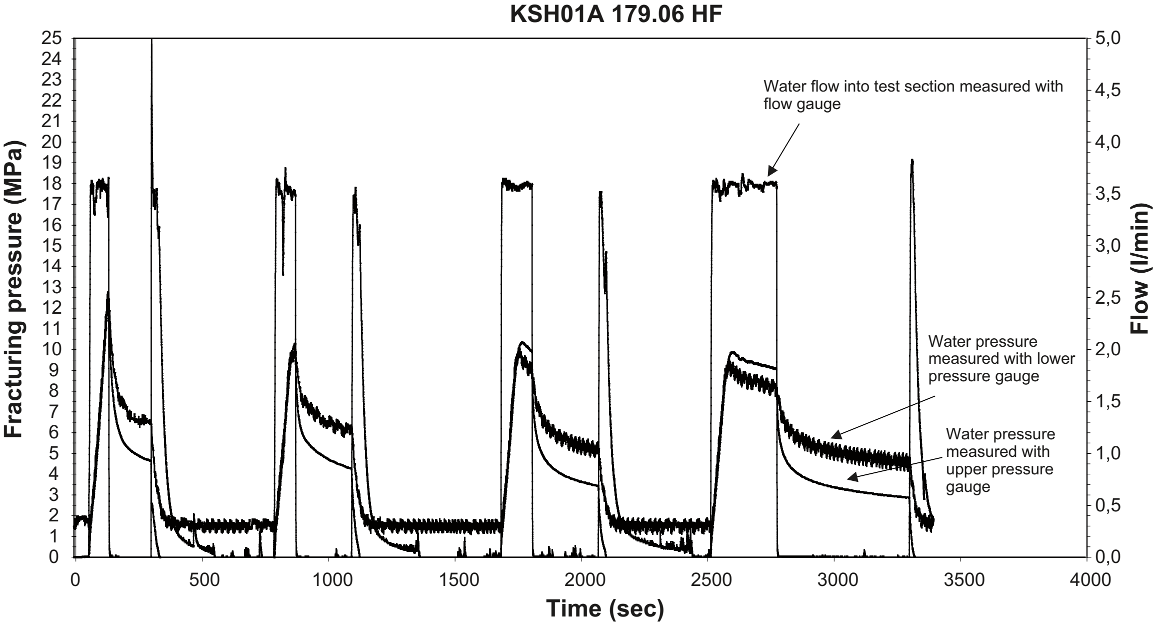


Figure 4-1. Typical pressure vs. time and flow vs. time plot for the HF tests performed in borehole KSH01A.

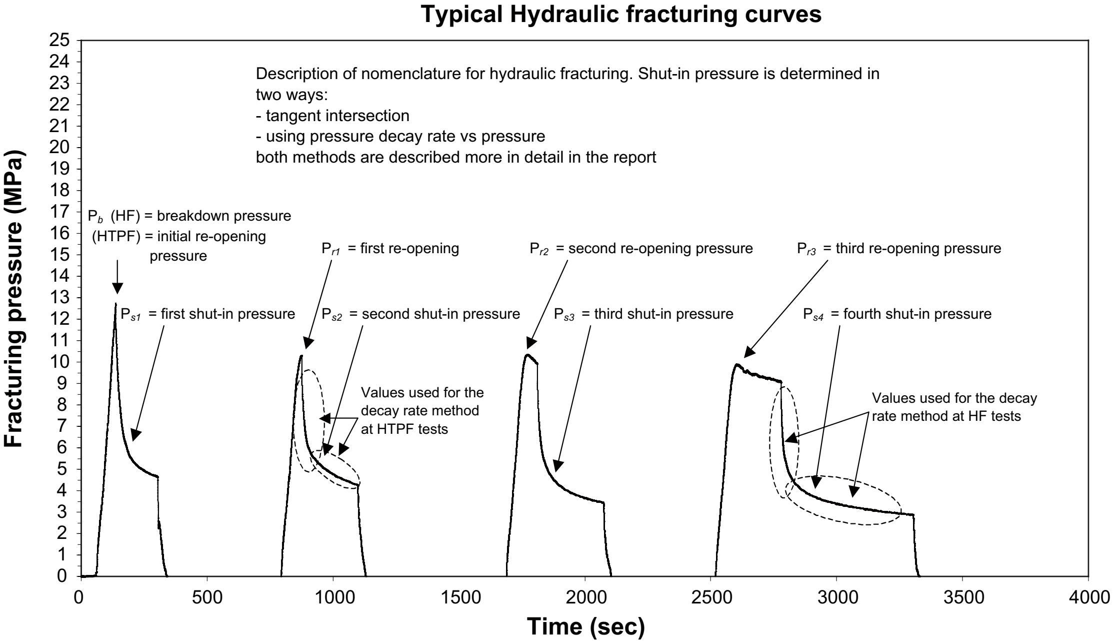


Figure 4-2. Nomenclature for HF and HTPF tests.

HTPF procedures in this project were performed according to the method description (SKB MD 182.003e, internal controlling document), as follows:

- Pressurisation of the sealed off section is conducted at a constant flow rate, normally lower than 1 l/min, resulting in an "opening pressure" of the fracture. The test line is shut-off immediately after breakdown is recorded, but not drained. The shut-in curve is normally recorded 3–4 minutes after shut-off and after that the test section is drained, see Figure 4-1 and Figure 4-2.
- The first pressurisation cycle is followed by four cycles where pressurisation is conducted at the same constant flow rate. However, the pumping time after reopening of the fracture is extended until a stable pump pressure is obtained. The test line is shut-off immediately after breakdown is recorded, but not drained. The shut-in curve is normally recorded 3–4 minutes after shut-off and after that the test section is drained.
- After the four pressurisation cycles, the test section is pressurized with a stepwise increasing flow while the steady state pressure for each flow step is recorded, also called "jacking test". To increase the certainties and/or better verify the shut-in pressure, the pressure is also decreased progressively in steps, in similar manner as for the increase of pressure, Figure 4-3.

4.2.5 Determination of fracture orientation (HF/HTPF)

To determine fracture orientation the following procedure was performed in this project (standard procedure), an imprint packer was prepared and a single shot camera unit was loaded and installed beneath the packer. The complete unit was lowered down the hole until the imprint packer was placed at the position of the created fracture from the HF test or the pre-existing fracture tested with the HTPF method.

The imprint packer was inflated with a packer pressure slightly higher than the recorded shut-in pressure for fracture. The pressure was held for 30 minutes and during that time a photo was taken of the magnetic compass in the camera unit. During these 30 minutes the rubber of the imprint packer penetrates into the fracture and a mark from the fracture was visible on the packer. After 30 minutes the imprint packer was hoisted (up) to surface.

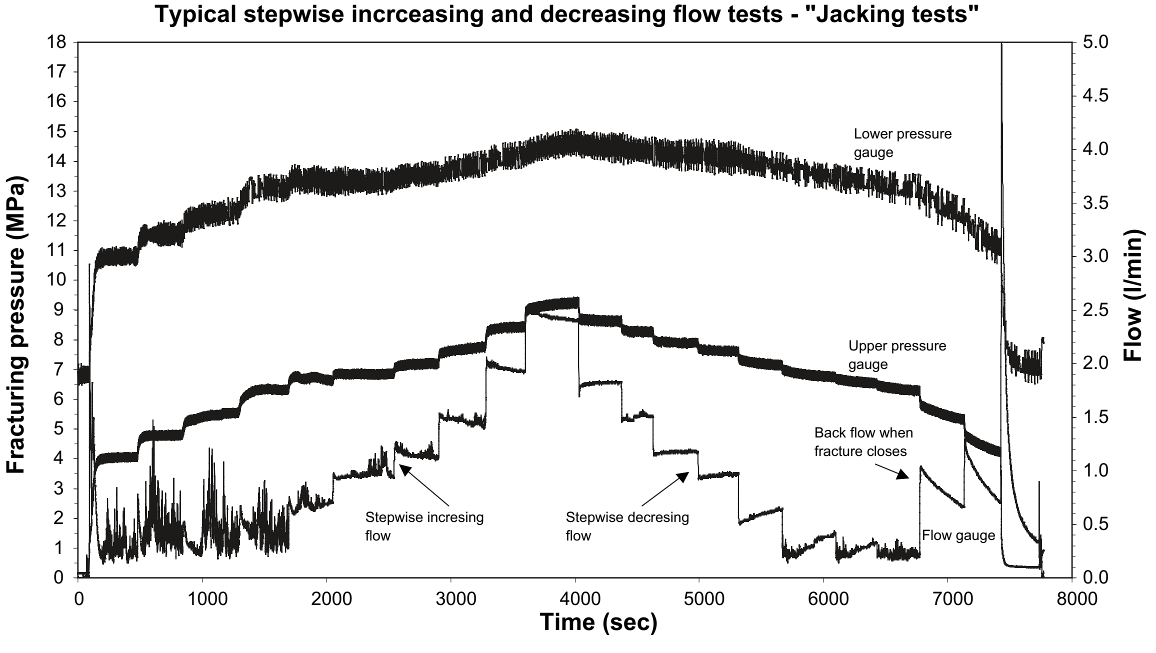


Figure 4-3. Typical increasing and decreasing flow and steady state pressure vs. time plot for the HTPF tests performed in borehole KSH01A.

The camera film was developed and the imprints of the fracture on the imprint packer was traced and marked on a transparent plastic sheet that was wrapped around the packer. This was done directly after the imprint packer had reached the surface. With the help of a tool face line marked along the complete unit of packer and camera unit, the imprints on the plastic sheet could then be given with respect to the magnetic north.

An imprint test was, in this work, performed for each hydraulic fracturing test to determine the fracture orientation at each HF test, here, totally six imprint tests.

Based on a decision taken by the Client, only two imprint tests were performed for the HTPF tests. These imprint test were done mainly to verify if the length calibration, done with measuring tape was correct. Therefore, one shallow and one deeply located fracture were chosen for imprint tests. It was specified that one of these fracture should be a sub-horizontal fracture and the other one should be a sub-vertical fracture. The results were also used to control if the determined orientation from rock cores could be considered correct, at least for these two fractures.

4.2.6 Determination of tensile strength

The tensile strength of the rock mass at the position for the hydrofracturing tests was, in this work, determined using two different methods: (1) the so-called “second breakdown method”, where the tensile strength was determined directly in field from the hydrofracturing graphs by using the difference between the breakdown and the re-opening pressure; and (2) the so-called “first breakdown method”, where the determination of the tensile strength was done in laboratory. For these types of tests, rock cores were taken from the position of hydraulic fracturing. For each of these cylindrical rock specimens, a borehole was drilled in the centre of the core along the centre line. Each test specimen was then held in position in a steel frame with a small uniaxial load and water was pumped into the borehole after the central part of the hole had been sealed of by “mini-packers”. No confining pressure was used during the tests to avoid horizontal stress influences on rock core while measuring the tensile strength of the rock /Doe et al. 1984, Ljunggren and Bjarnason 1990/. During these types of tests the water is normally pumped into the borehole with as low flow rate as possible due to the equipment, normally below 0.5 l/min, in this work, the flow was 0.2 l/min. During pumping the water pressure was equal to pressurisation pressure and flow was recorded. The cores chosen for laboratory tensile strength tests had the following geometry:

- length = 145–155 mm,
- outer diameter = 50 mm,
- centre hole diameter = 10 mm.

4.3 Data handling

The raw data include water pressure for both the fracturing and packer line and water flow data, all stored in computer data files and paper charts, checklists, and QA Report Forms from measurements. Routine data processing of measurement data involves importing the data file from the measurements into Microsoft Excel files for presenting pressure, flow vs. time graphs. Paper plots were, in this work, used as back-ups if the data from the registration for some reason was vague or doubtful.

A typical pressure vs. time and flow vs. time plot is shown below, normally, also the packer pressure is shown in the same chart. The nomenclature used for these types of tests is shown in Figure 4-2. The curves are similar for HTPF tests, and also, a typical increasing and decreasing flow chart is shown in Figure 4-3.

The results from imprint tests were gathered from the plastic sheets, and photos of magnetic compass readings from the fracture determination were stored into Microsoft Excel files and in the QA Report Forms.

4.4 Data analyses

4.4.1 HF

Field data are analyzed (and thereby the in situ stress determined) according to the classical theory for hydrofracturing in an impermeable, isotropic and linear elastic medium /Hubbert and Willis 1957/. Assuming a vertical borehole, the minimum and maximum stresses acting in a plane perpendicular to the borehole axis are calculated using data from the pressure records obtained from coaxial hydrofractures (planar fractures parallel with the borehole axis), see Figure 4-4. The classical theory /Hubbert and Willis 1957/ is based on the two-dimensional solution of the stresses around a hole in an infinitive plate.

The resisting stresses that must be exceeded to initiate failure are exerted by i) the tensile strength of the rock, and ii) the in situ stresses constituting the boundary loadings on the system. Hence, by recording the pressure at failure, the effect of the in situ stresses is obtained provided that the tensile strength is known. Once failure has occurred, water penetrates the fracture, and exerts an additional stress component on the internal surface of the fracture. The pressure required to propagate the hydrofracture will balance the normal stress acting across the fracture plane.

The fracture plane is normally parallel to the borehole axis, and two fracture traces are initiated simultaneously at diametrically opposite positions on the borehole periphery. The hydrofracture will initiate at the point, and propagate in the direction, offering the least confinement. The fracture will therefore develop in a direction perpendicular to the minimum rock stress, and hence stress directions can be resolved by determining fracture orientation.

In its conventional form, the method is two-dimensional; only the maximum and minimum normal stresses in the plane perpendicular to the borehole axis are determined. For a vertical borehole, these components are identical to the maximum and minimum horizontal stresses.

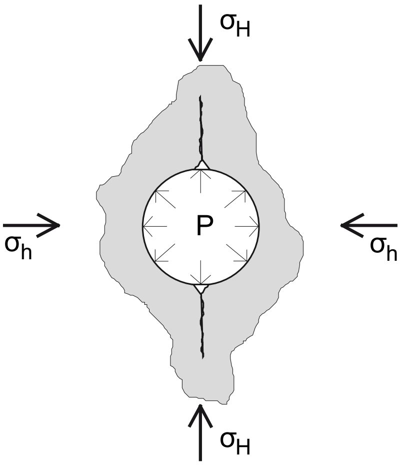


Figure 4-4. Schematic cross section of a borehole, illustrating the hydraulic fracturing method. If the borehole is vertical, σ_H *and* σ_h *are the maximum and minimum horizontal stresses respectively.*

The stresses are determined by the following procedure:

- The minimum horizontal stress is determined:
  - using the tangent intersection method described in /Enever and Chopra 1989, Klasson 1989/, the shut-in pressure is determined from pressure vs. time graphs, see Figure 4-5, or
  - using the decay rate method, plotting the rate of pressure decay against pressure, see Figure 4-6. The use of the Decay rate method is described in detail by /Lee and Haimson 1989, Wallroth 1991, Klasson 1989/.
- The determined shut-in pressure is then applied to (eq 1), below.
- The maximum horizontal stress is then determined by using either:
  - the first breakdown method, (eq 2), or
  - the second breakdown method, see (eq 3).
- For the first breakdown method, the tensile strength of the rock mass at the measured point is included, see (eq 2) /Hubbert and Willis 1957/. The tensile strength can be determined by laboratory tests, T_{lab}.
- When using the second breakdown method /Bredehoeft et al. 1976/ for determining the maximum horizontal stress, the tensile strength is excluded by using (eq 3), /Haimson and Cornet 2003/.

$$\sigma_h = P_s \qquad \text{(eq 1)}$$

$$\sigma_{HI} = 3 \cdot \sigma_h - P_b + T \qquad \text{(first breakdown method)} \qquad \text{(eq 2)}$$

$$\sigma_{HII} = 3 \cdot \sigma_h - P_r \qquad \text{(second breakdown method)} \qquad \text{(eq 3)}$$

where:

σ_h = minimum horizontal stress,

P_b = breakdown- or fracture initiation pressure (or initial opening pressure, HTPF),

P_s = shut-in pressure on the fracture plane,

P_r = re-opening pressure of the fracture plane,

σ_{HI} = maximum horizontal stress according to first breakdown method,

σ_{HII} = maximum horizontal stress according to second breakdown method and

T = tensile strength of intact rock under hydraulic fracturing conditions.

The tensile strength is determined from hydrofracturing test on unconfined cores in laboratory (T_{lab}), se Section 4.2.6. Regarding the scale effects, a scale factor, c, is used, according to (eq 4).

$$T = c \cdot T_{lab} \qquad \text{(eq 4)}$$

For the present work, the scale factor was chosen based on earlier documented experiences using a deterministic fracture mechanical approach based on the work of /Paris and Sih 1965/ and applied by /Doe et al. 1983/. The method has been used by a number of authors and is based on several parameters, such as core diameter, diameter of the drilled hole in the core, and maximum grain size. For the cores samples from borehole KSH01A, the maximum grain size is in the range of 2–6 mm. This gives a scale factor between 0.5 and 0.7 /Ljunggren and Bjarnason 1990, Klasson 1989/. An average scale factor of 0.6 was used in the following. The effect of choosing the scale factor somewhere between 0.5 and 0.7 is shown in Appendix E.

An estimation of the tensile strength T can be done in field (T_f) by using the difference between the value of breakdown (P_b) and first re-opening pressure (P_{r1}) at each test position, see (eq 5) and Figure 4-7. Although, it must be noted that, tensile strength used in the first break down method is intended to be the tensile strength determined from laboratory and not from the field. Therefore, using the results from field determined tensile stress is not the normal application of the first breakdown method (eq 2).

$$T = T_f = P_b - P_{r1} \qquad \text{(eq 5)}$$

It follows that the method requires a test volume of rock that is free from pre-existing structure that may influence failure load or direction of fracture development.

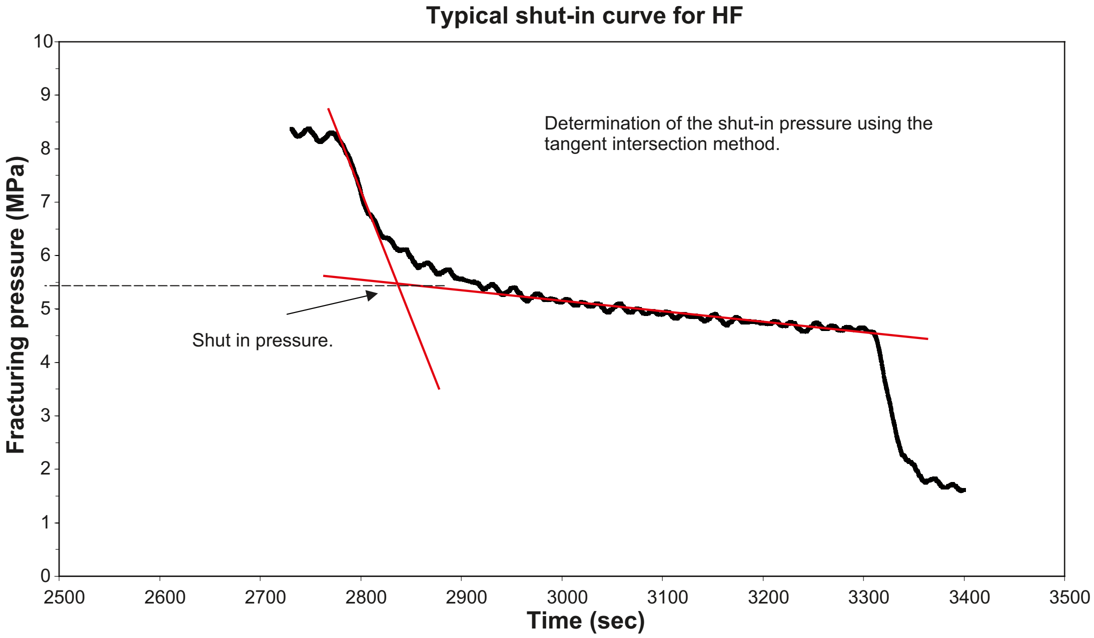


Figure 4-5. Determination of the shut-in pressure (P_s) with the tangent intersection method.

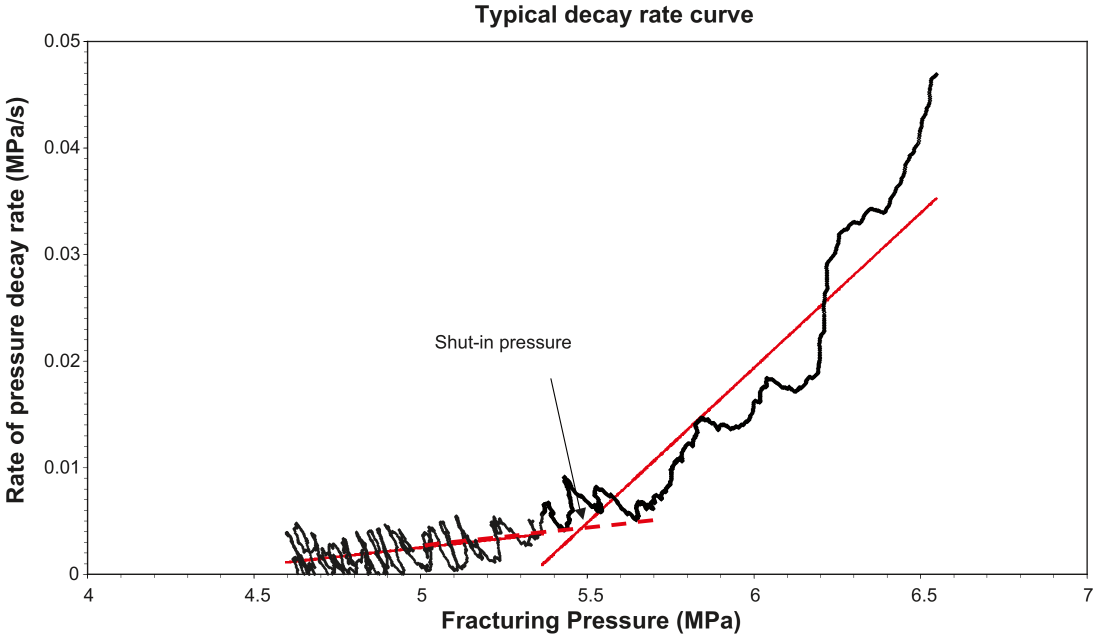


Figure 4-6. Determination of the shut-in pressure (P_s) with the decay rate method.

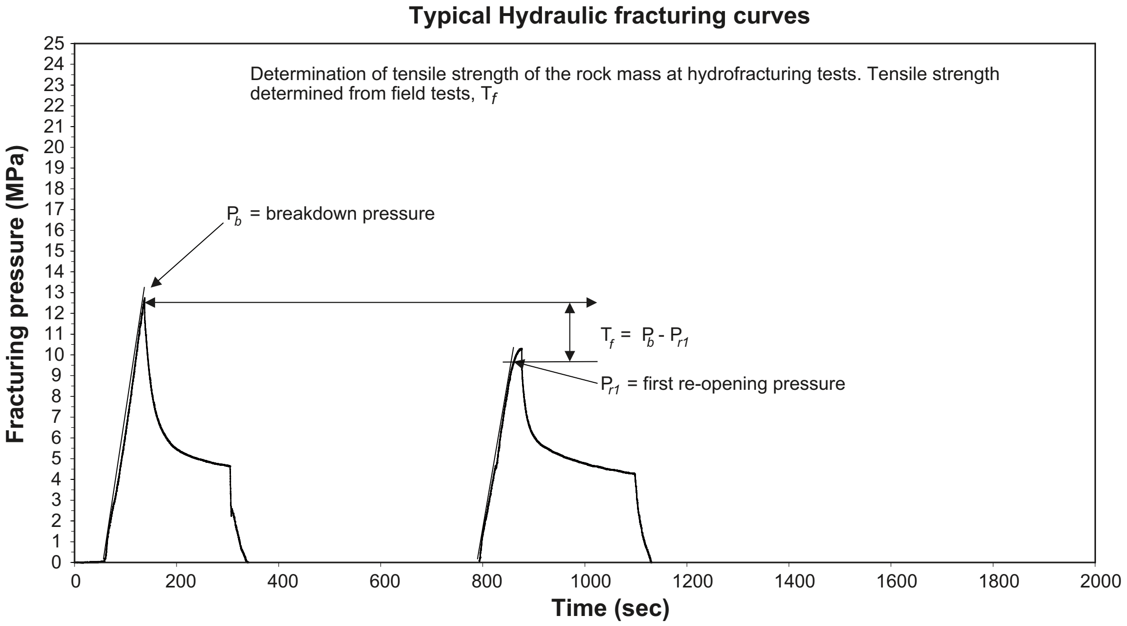


***Figure 4-7.** Determination of tensile strength from the field tests (T_f).*

4.4.2 HTPF

The HTPF method is based on the measurement of the normal stress acting across natural fracture planes with different orientations, a generalization of the HF-method. When pumping is conducted in a sealed-off section intersected by a natural fracture, the fracture opens and propagates in its own plane. To ensure this, the flow rate is kept low to prevent the initiation of a hydrofracture. The method is described in /Cornet 1993/ because of the limitations of the HF method.

As described above the HTPF method is based on the pressurisation of natural fractures intersecting the borehole. The testing of a natural joint depends on two parameters: (i) the ability to re-open the fracture, and (ii) the chances for hydrofracturing. These parameters depend on the stress magnitudes, the fracture orientation with respect to the principal stress directions, and the degree of healing of the pre-existing fracture.

The implementation and interpretation of HTPF tests follow those of classical hydraulic fracturing tests. Hence, for the HTPF tests, the following procedure is adopted:

- A "breakdown" pressure is recorded. However, in the case of HTPF, this value has no physical significance other then to confirm that an initial opening of the pre-existing fracture has been performed. The shut-in value gives a first estimate of normal stress (σ_n).
- Four re-opening cycles is recorded and used to govern the execution of the subsequent jacking test.
- The shut-in pressure is recorded. This corresponds to equilibrium between the hydraulic pressure in the fracture and the normal stress acting across the fracture plane.
- A stepwise increase and decrease of flow (jacking test) into the pre-existing fracture and the steady state pressure for each flow level is recorded. This is executed to increase the certainties and/or verify the shut-in pressure from previous pressurizations. A typical chart with analysis from hydraulic jacking tests is shown in Figure 4-8.

In the case of conventional hydraulic fracturing, the shut-in pressure (P_s) is a direct measure of the least horizontal stress (σ_h). In the case of an HTPF test where a pre-existing fracture is pressurised, the shut-in pressure provides the measurement of the normal stress (σ_n) acting across the fracture plane, as shown in (eq 6).

$$\sigma_n = P_s \qquad \text{(eq 6)}$$

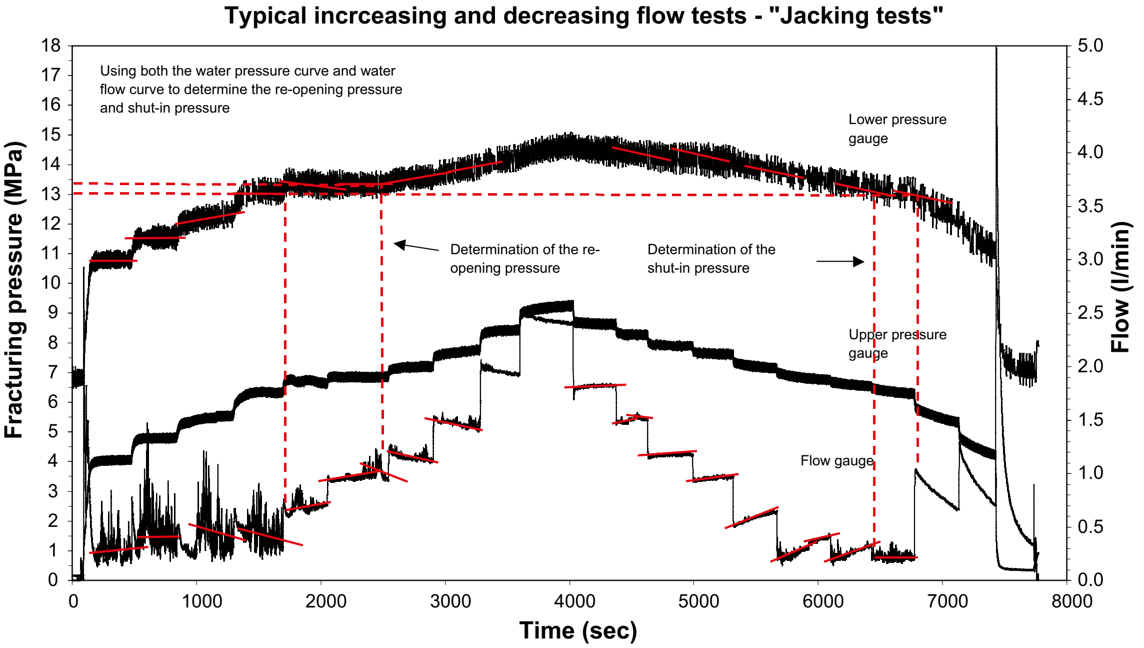


Figure 4-8. *Determination of the shut-in pressure from jacking tests, i.e. increasing and decreasing flow test.*

In HTPF tests, the shut-in pressure or normal stress from a pressure vs. time and flow vs. time curves is determined in the same way as for HF and is therefore not described here. However, the HTPF tests also include a hydraulic jacking or step pressure test as described above.

After the completion of a test, the following data are available:

- The depth of the test, z.
- The normal stress, σ_n.
- Parameters defining the natural fracture plane by its unit normal vector to the joint plane, referred to a fixed global coordinate system. In this work the orientation of the fractures are given by the Client.

For the analysis in this work, the following assumptions were made:

- The hole is vertical.
- One principle stress is parallel to the assumed direction of the borehole, i.e. vertical.
- The principle stress with vertical direction is 0.027 MPa/m.
- The orientation of the maximum horizontal stress is equal to the mean value of the results of stress direction determination of hydraulic fracturing tests between 510 and 530 m borehole length and is not rotating with depth.
- Non-fitting data is not affecting the results to any appreciable extent and is therefore still used in the analysis.
- The normal stress values obtained are assumed to correspond to the fracture identified from the BIPS measurements at the chosen test section.
- Standard deviation for included parameters is:
  - Depth = 0.1 m.
  - Dip/dip direction = 3°.
  - Minimum horizontal stress = 1 MPa.

The method used in the analysis (for this work) is the Integrated Stress Determination Method (ISDM). The method is described by /Cornet 1993/and /Ask 2004/ and is based on the least squares criterion /Tarantola and Valette 1982/.

5 Results

5.1 Overview

Measurements, both hydraulic fracturing (HF) and HTPF were attempted between 170 m and 750 m borehole length. Hydraulic fracturing was conducted at three main levels along the hole: around 180 m, 510–530 m and 710 m borehole length. The exact locations are shown below. The HTPF tests were distributed between 380 m and 745 m borehole length. In total, 6 hydraulic fracturing tests (HF) and 19 HTPF tests were performed. Additionally, six imprints were made for the HF tests (one for each test) and two imprints were made for the HTPF tests (at 380.57 m and 706.51 m borehole length). For further evaluation of the in situ stresses, the tensile strength of rock cores from the HF test sections was determined by laboratory tests.

A brief summary of conducted measurements is given in Table 5-1 and Table 5-2. All tests have been numbered as follows: *borehole number (or name), measurement depth, type of test*. Thus, e.g. test KSH01A 179.06 HF denotes borehole KSH01A, measurement at 179.06 m borehole length, and hydraulic fracturing test (HF). The measurement depth is the position for the centre of the test section. The distance from borehole collar to the centre of the test section is denoted as borehole length.

5.2 HF and HTPF test data

Results from all hydraulic fracturing tests are presented in the following chapter and in Appendix A. The results from all HTPF tests are also presented in the following chapter and in Appendix B. Imprint test results are shown in Appendix C. The results from tensile strength tests are presented in Appendix D. All original data are stored in the SKB database SICADA. Data are traceable in SICADA by the Activity Plan numer AP PS 400-04-015. The vertical stress presented below is the theoretical value corresponding to overburden pressure. A brief comparison between normal stress acting on sub-horizontal fractures and theoretical stress at same level is presented later in this report. The theoretical vertical stress is calculated with the gravitational acceleration set to 9.82 m/s^2 and the density of the rock assumed 2,700 kg/m^3.

Table 5-1. General test data from HF measurements in borehole KSH01A, Oskarshamn.

Test name	Hole length [m]	Vertical depth [m] *)	HF test	Imprint	Comments
KSH01A 179.06 HF	179.06	172.96	Yes	Yes	–
KSH01A 179.90 HF	179.90	173.77	Yes	Yes	–
KSH01A 510.10 HF	510.10	492.72	Yes	Yes	–
KSH01A 529.85 HF	529.85	511.80	Yes	Yes	Core taken for tensile strength determination could not be used due to damages.
KSH01A 530.75 HF	530.75	512.67	Yes	Yes	–
KSH01A 707.55 HF	707.55	683.44	Yes	Yes	–

*) Vertical depth using 75° inclination angle for the borehole.

Table 5-2. General test data from HTPF measurements in borehole KSH01A, Oskarshamn.

Test name	Hole length [m]	Vertical depth [m]*)	Strike natural fracture (°)**)	Dip natural fracture (°)**)	Comments
KSH01A 380.26 HTPF	380.26	367.40	262	83	Orientation is given from Client.
KSH01A 380.57 HTPF	380.57	367.60	87	21	As above.
KSH01A 394.48 HTPF	394.48	381.04	284	58	As above.
KSH01A 404.47 HTPF	404.47	390.69	29	76	As above.
KSH01A 411.01 HTPF	411.01	397.01	24	76	As above.
KSH01A 448.49 HTPF	448.49	433.21	110	56	As above.
KSH01A 651.39 HTPF	651.39	629.19	157	17	As above.
KSH01A 657.03 HTPF	657.03	634.64	73	24	As above.
KSH01A 669.22 HTPF	669.22	646.42	305	36	As above.
KSH01A 671.35 HTPF	671.35	648.47	343	34	As above.
KSH01A 675.08 HTPF	675.08	652.08	240	42	As above.
KSH01A 697.09 HTPF	697.09	673.34	64	21	As above.
KSH01A 705.75 HTPF	705.75	681.70	174	27	As above.
KSH01A 706.51 HTPF	706.51	682.44	293	74	As above.
KSH01A 715.40 HTPF	715.40	691.02	294	68	As above.
KSH01A 730.01 HTPF	730.01	705.14	208	80	As above.
KSH01A 732.63 HTPF	732.63	707.67	166	87	As above.
KSH01A 739.11 HTPF	739.11	713.93	231	65	As above.
KSH01A 744.18 HTPF	744.18	718.82	35	11	As above.

*) Vertical depth using 75° inclination angle for the borehole.

**) From BIPS measurements.

5.2.1 HF

At 510.10 m borehole length the lower pressure gauge gave unstable values, probably due to moisture inside the gauge, but the test could still be completed. Afterwards the system was hoisted up to surface and the lower pressure gauge was dismantled and dried. A similar problem occurred for the HF test at level 707.55 m but of less magnitude and the same action was taken as done at the previous occasion. Since the water pressure was monitored with two gauges (one down in the borehole and one on surface), no information was lost during these tests and both tests were then judged successful. All the other HF tests including all imprint tests were performed without any incidents.

5.2.2 HTPF

Generally, all HTPF tests and data recording from 380.26 and to 675.08 m borehole length were successfully. At level 697.09 m test depth, moisture in the lower pressure gauge during the test gave unstable values but the test was completed. The lower pressure gauge was dismantled and dried and the HTPF tests could be continued. Imprint tests were performed on level 380.57 and 706.51 m and compared with the results from BIPS logging of the borehole. The results indicated that the length calibration of the hose was correct.

For the “jacking test” at 706.51 m test depth an electrical pulse shut down the monitoring computer at the start of the decreasing flow part of the test. The test could be completed since the chart recorder backup was functioning. The jacking tests in borehole KSH01A were all performed with a stepwise increasing and decreasing flow/pressure. Afterwards, a new flow/pressure decrease testing was performed and recorded digitally at 706.51 m borehole length.

5.2.3 Imprint tests

All imprint tests went well. A total of eight imprint tests were performed during the field period, one for each HF test, and two of the client selected HTPF tests sections. The results from the imprint tests are shown in Table 5-3.

For all vertical fractures, two fracture traces were observed diametrically on the imprint packer. For sub-vertical and inclined fractures the traces were visible all the way around the imprint packer.

5.2.4 Tensile strength determination

Five core samples were selected for determination of the tensile strength in laboratory, see Table 5-4. The core sample from 697.88 m is representing rock mass at level 707.55 m since no cores are left from this position (707–708 m) of the borehole. The core sample from level 697.88 m was chosen because it represents a rock with similar geology as the rock mass at 707 to 708 m depth. The core samples were partly prepared on site and finally prepared and tested at Luleå University of Technology. One core sample (529.85 m borehole length) broke during transport and could not be used. The results are presented below; see Table 5-4, along with comparison between T_f and T_{lab}, the *c*-factor is **not** included to the T_{lab} values in Table 5-4. For determining T_f, (eq 5) has been used.

Table 5-3. Strike of tested factures determined from imprint tests of fractures created from HF or pre-existing fractures in HTPF tests in borehole KSH01A.

Test name	Hole length [m]	Vertical depth [m] *)	Strike fracture [°]	Comments
HF tests				
KSH01A 179.06 HF	179.06	172.96	111	Sub-vertical fracture, an additional. sub-vertical fracture was observed.
KSH01A 179.90 HF	179.90	173.77	116	Vertical fracture, an additional vertical fracture was observed.
KSH01A 510.10 HF	510.10	492.72	136	Vertical fracture.
KSH01A 529.85 HF	529.85	511.80	119	Vertical fracture.
KSH01A 530.75 HF	530.75	512.67	133	Vertical fracture, an additional vertical fracture was observed.
KSH01A 707.55 HF	707.55	683.44	117	Vertical fracture, some additional vague fractures were observed.
HTPF tests				
KSH01A 380.26 HTPF	380.26	367.30	–	Inclined fractures, imprints from a number of sub-horizontal fractures.
KSH01A 706.51 HTPF	706.51	682.44	–	Measured strike 295°, dip 75° from imprint test, however, more than one fracture is detected at the position.

*) Vertical depth using 75° inclination angle for the borehole.

Table 5-4. Comparison between T_{lab} and T_f.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_f [MPa]	Comments
179.06	179.50	17.1	3.9	T_{lab} – tests gave vertical fracture.
510.10	510.35	6.9	2.2	T_{lab} – tests gave sub-horizontal fracture
529.85	529,85		3.5	Broken at arrival to laboratory
530.75	531.10	13.7	1.2	T_{lab} – tests gave sub-vertical fracture
707.55	697.88	11.3	0.8	T_{lab} – tests gave sub-horizontal fracture

In general, the test performances for all tests were successful but for the two samples taken from 510.35 and 697.88 m borehole length the results were not successful. At these two samples, sub-horizontal fractures were achieved from the hydrofracturing test and these results were then discarded. Because of the limited number of tests (only one representing each level) the mean value of the two remaining results from tensile strength tests were chosen to represent the mean laboratory tensile strength of all samples. The mean value, T_{lab} = 15.5 MPa, and a scale factor c equal to 0.6 results in a tensile strength, T = 9.3 MPa. This value is used for determination of the maximum horizontal stress, σ_H with the first breakdown method.

5.3 In situ stress state

5.3.1 Measured results from HF and HTPF tests

The shut-in pressure has been determined using the two methods,

- tangent intersection method and,
- pressure decay rate method.

Both are described in Section 4.4.1. Both systems have been used for determination of the shut-in pressure for HF as well as for HTPF tests. The difference in result between those two methods is small, see Table 5-5 and Table 5-7. Due to very dense sampling of data (one sampling/50 millisecond), the data set became saw-tooth shaped in a very small time scale. Therefore, for determination of shut-in pressure using the pressure decay rate method, a “floating mean value” of the shut-in part of each curve is used to be able to derivate the pressure decrease with time. A regression analysis was then performed on the bilinear curve that was achieved.

There are no exact instructions at the method description (SKB MD 182.003e) or the ISRM Suggested Method for rock stress estimation /Haimson and Cornet 2003/ from which test cycle between the second to fifth cycle the shut-in pressure should be taken. Therefore, an earlier often used and known procedure has been used:

- Data for determining the shut-in pressure and re-opening pressure from HF tests are taken from the fourth test cycle. The fourth test cycle is used to eliminate the influence of cohesion along the surface of the new fracture.
- Data for determining the shut-in pressure from HTPF tests are taken from the second test cycle. The reason for using the second test cycle for determination of shut-in pressure is to avoid that the pre-existing fracture propagates too far and the orientation of it rotate and/or the tested fracture connects to other fractures /Ask 2001/, (Ask D 2004, personal communication).

The results of determined values for P_b, P_r and P_s are shown in Table 5-6.

To be consistent, the result from tangent intersection method has been chosen to be used for determination of the minimum horizontal stress, using (eq 1). The results from the pressure decay rate method and hydraulic jacking tests have been used as a control for reliability of the result both for HF and HTPF tests.

Table 5-5. Comparison between achieved P_s from tangent intersection and decay rate method.

Test name	Shut-in pressure tangent intersection method [MPa]*)	Shut-in pressure pressure decay rate method [MPa]*)
KSH01A 179.06 HF	5.4	5.4–5.5
KSH01A 179.90 HF	5.4	5.3–5.4
KSH01A 510.10 HF	18.7	N/A **
KSH01A 529.85 HF	10.5	10.2–10.3
KSH01A 530.75 HF	10.5	10.6–10.7
KSH01A 707.55 HF	12.9	N/A **

*) Determined from the fourth test cycle.

**) Comments for each result see Appendix A.

Table 5-6. Summary of measured results from HF tests in Borehole KSH01A.

Test name	P_b, breakdown pressure [MPa]	P_r, re-opening pressure [MPa]*)	P_s, shut-in pressure tangent intersection method [MPa]*)
KSH01A 179.06 HF	12.4	8.0	5.4
KSH01A 179.90 HF	10.2	6.5	5.4
KSH01A 510.10 HF	26.0	22.0	18.7
KSH01A 529.85 HF	14.7	12.0	10.5
KSH01A 530.75 HF	12.8	11.0	10.5
KSH01A 707.55 HF	14.0	12.0	12.9

*) Determined from the fourth test cycle.

Table 5-7. Comparison between shut-in pressure determination at HTPF tests in borehole KSH01A.

Test name	Shut-in pressure stepwise pressuration [MPa]	Shut-in pressure tangent intersection method [Mpa]*)	Shut-in pressure pressure decay rate method [MPa]*)
KSH01A 380.26 HTPF	7.7–8.2	7.7	7.7–7.8
KSH01A 380.57 HTPF	8.6–10.0	9.8	9.9–10.0
KSH01A 394.48 HTPF	6.0–7.4	7.2	7.3–7.4
KSH01A 404.47 HTPF	12.7–14.8	14.2	13.7–13.8
KSH01A 411.01 HTPF	7.4–7.8	6.6	7.0–7.1
KSH01A 448.49 HTPF	15.1–17.0	14.5	13.9–14.0
KSH01A 651.39 HTPF	15.5–17.5	17.3	17.4–17.5
KSH01A 657.03 HTPF	15.1–16.5	14.5	14.7–14.8
KSH01A 669.22 HTPF	11.7–12.0	12.5	12.4–12.5
KSH01A 671.35 HTPF	13.7–14.2	13.0	13.2–13.3
KSH01A 675.08 HTPF	13.1–14.0	11.7	11.6–11.7
KSH01A 697.09 HTPF	12.6–14.5	14.0	13.9–14.0
KSH01A 705.75 HTPF	13.0	13.0	12.8–12.9
KSH01A 706.51 HTPF	12.9–13.6	13.0	12.7–12.8
KSH01A 715.40 HTPF	13.0–13.2	13.6	13.5–13.6
KSH01A 730.01 HTPF	13.0–16.5	17.0	17.1–17.2
KSH01A 732.63 HTPF	14.8–16.2	16.6	17.3–17.4
KSH01A 739.11 HTPF	12.9–13.1	13.2	13.9–14.0
KSH01A 744.18 HTPF	13.7–14.0	14.1	14.1–14.2

*) Determined from the second test cycle.

5.3.2 Horizontal stresses determined from HF

The results from the HF measurements and determination of maximum and minimum horizontal stress, using various methods are shown in Table 5-8 to Table 5-10. Using the first breakdown method for determining the maximum horizontal stress, the in situ stresses were as shown in Table 5-8 using the (eq 1), (eq 2) and (eq 4) and the results shown in Table 5-6. A mean value of T_{lab} = 15.5 MPa was used and the scale factor *c* was set to 0.6.

When using the second breakdown method for determining the maximum horizontal stress the tensile strength was excluded by using (eq 1) and (eq 3). The in situ stresses determined with the tangent intersection method (to determine σ_h) and second breakdown method is shown in Table 5-9. The orientation of the horizontal stresses, are shown Table 5-10 below. All orientations are given relative to magnetic north.

Table 5-8. Horizontal stresses calculated from HF tests and using the first breakdown (with T_{lab}) method for borehole KSH01A.

Test name	Hole length [m]	Vertical depth [m] **)	$\sigma_{H(I)}$ [MPa]	σ_h [MPa]	σ_v [MPa]*)
KSH01A 179.06 HF	179.06	172.96	13.1	5.4	4.6
KSH01A 179.90 HF	179.90	173.77	15.0	5.4	4.6
KSH01A 510.10 HF	510.10	492.72	39.4	18.7	13.1
KSH01A 529.85 HF	529.85	511.80	26.1	10.5	13.6
KSH01A 530.75 HF	530.75	512.67	28.0	10.5	13.6
KSH01A 707.55 HF	707.55	683.44	34.0	12.9	18.1

*) Theoretically calculated vertical stress from overburden weight.

**) Vertical depth using 75° inclination angle for the borehole.

Table 5-9. Horizontal stresses calculated from HF tests using the second break down method for borehole KSH01A.

Test name	Hole length [m]	Vertical depth [m] **)	$\sigma_{H(II)}$ [MPa]	σ_h [MPa]	σ_v [MPa]*)
KSH01A 179.06 HF	179.06	172.96	8.2	5.4	4.6
KSH01A 179.90 HF	179.90	173.77	9.7	5.4	4.6
KSH01A 510.10 HF	510.10	492.72	34.6	18.7	13.1
KSH01A 529.85 HF	529.85	511.80	19.9	10.5	13.6
KSH01A 530.75 HF	530.75	512.67	20.5	10.5	13.6
KSH01A 707.55 HF	707.55	683.44	26.7	12.9	18.1

*) Theoretically calculated vertical stress from overburden weight.

**) Vertical depth using 75° inclination angle for the borehole.

Table 5-10. Bearing of maximum and minimum horizontal stresses determined from imprint tests after HF tests in borehole KSH01A.

Test name	Hole length [m]	Vertical depth [m] *)	Bearing σ_H [°]	Bearing σ_h [°]
KSH01A 179.06 HF	179.06	172.96	111	21
KSH01A 179.90 HF	179.90	173.77	116	26
KSH01A 510.10 HF	510.10	492.72	136	46
KSH01A 529.85 HF	529.85	511.80	119	29
KSH01A 530.75 HF	530.75	512.67	133	43
KSH01A 707.55 HF	707.55	683.44	117	27

*) Vertical depth using 75° inclination angle for the borehole.

5.3.3 Horizontal stresses determined from HTPF

Measurement results, orientation of the normal stress acting on the pre-existing fractures submitted to HTPF tests, and the measured normal stress acting on the natural fractures are shown in Table 5-11.

From the combination of input data from Table 5-9 and the HF results, maximum and minimum horizontal stresses were calculated from the HTPF measurements, using the Integrated Stress Determination Method (ISDM); /Ask 2004/. The results are shown in Table 5-12.

A comparison between theoretically calculated vertical stress and actually measured normal stress appearing on sub-horizontal fractures was performed. Only fractures with a dip angle less than 25° from the horizontal plane was included in the comparison, se Table 5-13.

Table 5-11. Results from HTPF measurements in borehole KSH01A, Oskarshamn.

Test name	Hole length [m]	Vertical depth [m]*)	Dip direction σ_n [°]	Dip σ_n [°]	σ_n [MPa]
KSH01A 380.26 HTPF	380.26	367.30	172	7	7.7
KSH01A 380.57 HTPF	380.57	367.60	–3	69	9.8
KSH01A 394.48 HTPF	394.48	381.04	194	32	7.2
KSH01A 404.47 HTPF	404.47	390.69	–61	14	14.2
KSH01A 411.01 HTPF	411.01	397.01	–66	14	6.6
KSH01A 448.49 HTPF	448.49	433.21	20	34	14.5
KSH01A 651.39 HTPF	651.39	629.19	73	73	17.3
KSH01A 657.03 HTPF	657.03	634.64	66	66	14.5
KSH01A 669.22 HTPF	669.22	646.42	215	54	12.5
KSH01A 671.35 HTPF	671.35	648.47	253	56	13.0
KSH01A 675.08 HTPF	675.08	652.08	150	48	11.7
KSH01A 697.09 HTPF	697.09	673.34	–26	69	14.0
KSH01A 705.75 HTPF	705.75	681.70	84	63	13.0
KSH01A 706.51 HTPF	706.51	682.44	203	16	13.0
KSH01A 715.40 HTPF	715.4	691.02	204	22	13.6
KSH01A 730.01 HTPF	730.01	705.14	118	10	17.0
KSH01A 732.63 HTPF	732.63	707.67	76	3	16.6
KSH01A 739.11 HTPF	739.11	713.93	141	25	13.2
KSH01A 744.18 HTPF	744.18	718.82	–55	79	14.1

*) Vertical depth using 75° inclination angle for the borehole.

Table 5-12. Horizontal stresses calculated from HTPF tests and theoretically determined vertical stress in borehole KSH01A.

Calculated level	σ_H [MPa]	σ_h [MPa]	σ_v [MPa]	Bearing σ_H [°]	Bearing σ_h [°]
100	5.8	**4.7***	2.7	120	30
200	7.3	**6.1***	5.4	120	30
300	8.8	**7.6***	8.1	120	30
400	10.3	**9.0***	10.8	**120***	**30***
500	11.8	**10.4***	13.5	**120***	**30***
600	13.3	**11.9***	16.2	120	30
700	14.8	**13.3***	18.9	120	30
800	16.3	**14.7***	21.6	120	30
900	17.8	**16.2***	24.3	120	30

*) Bold values most reliable.

Table 5-13. Comparison between measured normal stress on pre-existing fractures and theoretical determined vertical stress.

Test name	Hole length [m]	Vertical depth [m]*)	Strike natural fracture [°]	Dip natural fracture [°]	Dip σ_n [°]	Measured σ_n [MPa]	Theoretical determined σ_v [MPa]
KSH01A 380.57 HTPF	380.57	367.60	87	21	69	9.8	9.7
KSH01A 651.39 HTPF	651.39	629.19	157	17	73	17.3	16.7
KSH01A 657.03 HTPF	657.03	634.64	73	24	66	14.5	16.8
KSH01A 697.09 HTPF	697.09	673.34	64	21	69	14.0	18.8
KSH01A 744.18 HTPF	744.18	718.82	35	11	79	14.1	19.1

*) Vertical depth using 75° inclination angle for the borehole.

The result shows similarities, with differences of less then 15% between measured normal stress and theoretically calculated stress down to 657 m borehole depth. Below 657 m the differences are somewhat larger.

5.3.4 Summary of the determination of the minimum and maximum horizontal stresses from HF and HTPF tests

A summary of the results of the maximum and minimum horizontal stress determined from both HF and HTPF is shown in Table 5-14 together with theoretically calculated vertical stress. The calculated levels, shown at Table 5-14 in column "Calculated level", where all given by the computer program used in the analysis. The computer program used for ISDM-method (described by /Ask 2004/) was programmed to show the results at these chosen levels for the HTPF-analysis.

Table 5-14. Summary of horizontal and vertical stresses calculated from HF and HTPF tests in borehole KSH01A.

Vertical depth [m]	Calculated level [m]	$\sigma_{H(I)}$ from HF [MPa]	$\sigma_{H(II)}$ from HF [MPa]	σ_H from HTPF [MPa]	σ_h from HF [MPa]	σ_h from HTPF [MPa]	σ_v [MPa]	Bearing σ_H [°]	Bearing σ_h [°]
	100			*5.8*		**4.7**	2.7	*120*	*30*
172.96		13.1	*8.2*		5.4		4.6	111	21
173.77		15.0	*9.7*		5.4		4.6	116	26
	200			*7.3*		**6.1**	5,4	*120*	*30*
	300			*8.8*		**7.6**	8.1	*120*	*30*
	400			*10.3*		**9.0**	10.8	**120**	**30**
492.72		39.4	*34.6*		18.7		13.1	136	46
	500			*11.8*		**10.4**	13.5	**120**	**30**
511.80		26.1	*19.9*		10.5		13.6	119	29
512.67		28.0	*20.5*		10.5		13.6	133	43
	600			*13.3*		**11.9**	16.2	*120*	*30*
683.44		34.0	*26.7*		12.9		18.2	117	27
	700			*14.8*		**13.3**	18.9	*120*	*30*
	800			*16.3*		**14.7**	21.6	*120*	*30*
	900			*17.8*		**16.2**	24.3	*120*	*30*

Italic values not reliable from the HTPF analysis.

Bold values reliable from the HTPF analysis.

The minimum horizontal stress indicates an almost linear trend both for HF and HTPF data, with a magnitude of 10–12 MPa in the region of 500 to 600 m depth below surface. It should however, be noticed that the results of HTPF is depending on the HF results since these have been used as input values in the HTPF analysis. The maximum horizontal stress determined by the second breakdown method from HF tests shows an fairly linear trend with depth with a magnitude of 20–22 MPa at depths around 500 m below surface, with the exception of one result (492.72 m vertical depth). The first breakdown method used on HF data shows, however, more scattered results and also higher stress magnitudes, between 25 and 30 MPa. This is around 30–40% higher in comparison with the results from second breakdown method at 500 m level, Figure 5-1. The maximum horizontal stress determined from HTPF is not shown in the figure since the results are uncertain.

The orientation of horizontal stresses is consistently determined from HF tests. These orientations coincide with the results from HTPF test in the 500 m level region. In summary, it appears that the maximum horizontal stress has a bearing of 111° to 136° relative to magnetic north, i.e. E-W to ESE-WNW. The magnitudes of the maximum horizontal stresses are quite moderate, probably somewhat above 20 MPa but no higher than 25–30 MPa for the maximum horizontal stress and between 10 to 12 MPa for the minimum horizontal stress, around 500 m below surface.

5.4 Discussion

5.4.1 The results from HF

Since the borehole has a dip around 75 degrees along most of its length according to the single shot magnetic compass, it is in contrary to BIPS log by /Aaltonen et al. 2003/ giving a rotation in dip 81°–68° versus depth. Using the average BIPS-direction, the methods are fairly consistent. In the following discussion section, each test position will only be referred to “vertical depth” and **not** also to “borehole length” as done in previous section of the report. The effect on the stress analysis, assuming a vertical borehole coinciding with one principal stress direction, is regarded minor. An indication that this assumption may not be correct was found at 682.44 m vertical depth where en echelon fractures were observed.

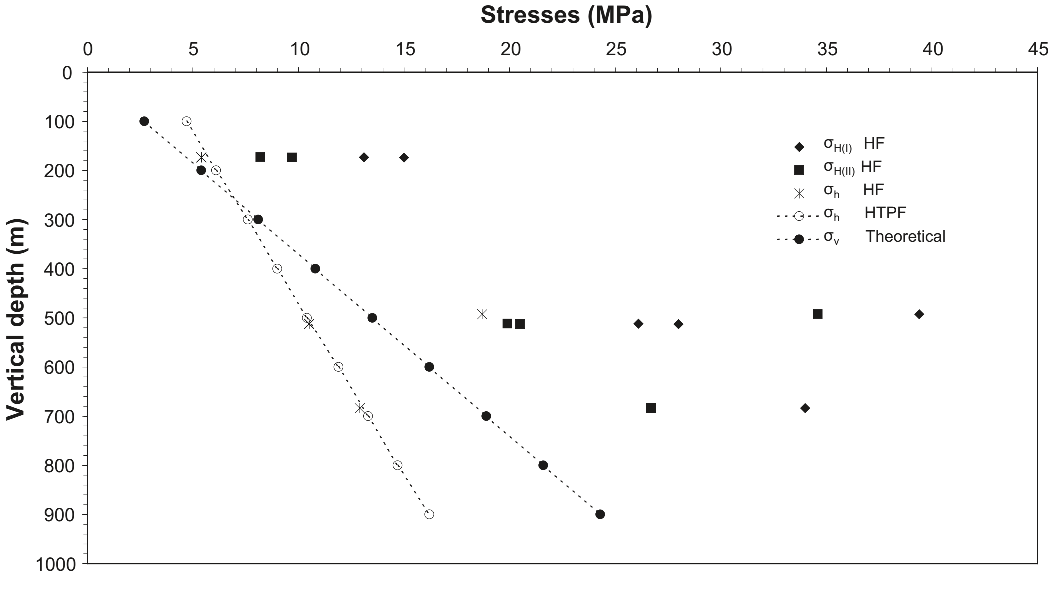


Figure 5-1. Summary of maximum and minimum horizontal stresses determined with HF and minimum horizontal stress with HTPF at borehole KSH01A. Vertical stress correspond to the weight of the overburden rock mass.

One measurement from the HF tests shows unexpectedly high values of maximum and minimum stresses, see charts in Appendix A. This local stress heterogeneity may possibly be explained by geological factors, but this is outside the scope of the report.

Comparing the two methods for determining the maximum horizontal stresses, the results using the first breakdown method are more scattered with higher σ_H-magnitudes. Other drawbacks with the first breakdown method are (in this project) the small number of tests available for tensile strength determination, and the uncertainty in choice of scale factor, a comparison is shown in Appendix E. However, there are drawbacks with the second breakdown method as well. These include i) the assumed stress field around the borehole after fracture initiation is not correct /Rutqvist et al. 2000/; ii) the compressibility of the hydraulic test equipment does not allow correct estimation of P_r /Ito et al. 1999/; and iii) the re-opening pressure has been found to be flow rate dependent /Cornet 1993, Rutqvist 1995, Rutqvist et al. 2000/. However, both methods have drawbacks, but only the results using the second breakdown method have been presented in the following discussion section since the results from this method are less scattered.

5.4.2 The results from HTPF

The results from the HTPF should be used with caution since some of these are mismatching with results from hydraulic fracturing (Ask 2004, personal communication). The facts that there are no imprint tests on most of the pre-existing fracture, submitted to HTPF, also make the analysis from the HTPF test uncertain.

In the analysis with HTPF the borehole is assumed completely vertical (dip 90 degrees), although the borehole has a dip between 75 and 76 degrees. The HTPF solution contains a number of heterogeneous data, as:

- The results from HF tests at 492.72 m vertical depth in comparison with the rest of data.
- Tests at 367.60 and 381.04 m vertical depth indicate decreasing stresses with depth.
- At 367.60 and 433.21 m vertical depth tests indicate strongly increasing stresses with depth.
- Tests at 390.69 and 397.01 m vertical depth shows completely different results although similar fractures.
- Tests at 646.42 and 648.47 m vertical depth indicate almost non-existent difference between maximum and minimum horizontal stress.
- At 705.14 and 707.67 m vertical depth tests indicate almost non-existent difference between maximum and minimum horizontal stress.
- At 718.82 m vertical depth the analysis indicate vertical stress equal to 13 MPa, which is considerably less than theoretical vertical stress around 18.5 MPa.

The HTPF results for minimum horizontal stress are in accordance with the HF results. Thus, are these HTPF results regarded to be considered reliable. This holds especially for the results between 400 and 500 m vertical depth.

Since the gradient for the minor horizontal stress has a low standard deviation it is likely that the determined minor stresses for regions both above and below 400–500 m are reliable. This is not the case for the major horizontal stress and its direction determined from the HTPF tests. The results for the major horizontal stresses are assumed to have a low accuracy since these results are not in accordance with the HF results, regarding both the magnitude and direction of the stress.

The accuracy of the results could possibly have been improved if imprints had been made on each of the tested pre-existing fractures. There is always the possibility that more than one fracture in the test section have been opened during the test, pre-existing or induced, which gives an incorrect result of the HTPF test. There is also a risk that, within a group of open or healed fractures, the fracture that is opened at the core, on surface, is not opening in the borehole while testing, but another, close located fracture is instead opened. Again, the assumed orientation for the pre-existing fracture submitted to HTPF can be wrong and thereby giving a misleading value, for both magnitude and direction, of the primarily major horizontal stress.

If an imprint test had been made for each HTPF-test, there would have been a possibility to determine each fracture orientation at each test section. And, if there were any doubts about what fracture that had opened during the test due to positioning of the packers, iterations during the analysis (testing of different fracture orientations) could have been done to establish what fracture orientation were the most possible to be opened from water pressure and giving the most reliable result of the horizontal stresses in the analysis.

Together with uncertainties of what pre-existing fracture has been tested at HTPF tests, a majority of these tests indicate a large difference between breakdown pressure and reopening pressure, which indicate that new fractures may have been induced. Only four tests indicate a small pressure difference (≤ 1 MPa) between the first and second pressurization cycle. Thus, it is suggested that most HTPF tests have induced fractures, rendering the orientations for each HTPF test section obtained from the BIPS log doubtful. Most of the HTPF tests with distinct breakdown indicate a well-defined stress increase versus depth, which if fractures indeed have been induced, may be regarded as an estimate of minimum horizontal stress. Two exceptions are the tests at 390.69 m and 433.21 m vertical depth, which according to the orientation defined by the BIPS log would measure the normal stress as a function of primarily σ_H and σ_v and primarily σ_h and σ_v, respectively. It is suggested that fractures in these cases were indeed induced, but the pre-existing fractures were also opened and dominating the pressure-flow response in the test section. This phenomenon has been observed in hydraulic stress measurements in e.g. Äspö HRL /Ask 2001/.

Two of the four HTPF tests on pre-existing fractures are sub-horizontal (according to the core log) and indicate a good fit with theoretical vertical stress (367.60 and 629.19 m vertical depth). The other two tests on pre-existing fractures correspond approximately to σ_h and σ_H according to the BIPS log (691.02 m and 705.14 m vertical depth, respectively).

5.4.3 Summary of discussion and comparison with other measurements

The HF and HTPF with marked breakdown, indicates, a well-defined trend of the data (see Figure 5-2) disregarding heterogeneous HF-data at 492.72 m vertical depth.

As discussed in the previous section is only four HTPF tests undoubtedly opened a pre-existing fracture whereas 15 tests likely induced new fractures. Two out of four the pre-existing fractures are sub-horizontal (compared with Table 5-14) and indicate a good fit with the theoretical vertical stress. The other two tests correspond approximately to σ_v and σ_H according to the BIPS log. Two of the HTPF tests that likely resulted in new fracture development indicate a normal stress in excess of the theoretical vertical stress.

It is suggested that this trend likely correspond to minimum horizontal stress, which is almost 5 MPa lower than the theoretical vertical stress at 680 m depth (based on data between 630 and 720 m depth).

The determined minimum horizontal stress results from both HF and HTPF are in accordance to results from overcoring (OC) stress measurements conducted in borehole KAV04 /Sjöberg 2004/. Maximum horizontal stress determined in KSH01A with hydraulic fracturing methods is somewhat higher compared with the maximum horizontal stresses measured in KAV04 with the overcoring (OC) method. Maximum horizontal stress determined with the second breakdown method fits better with the results from OC-tests in KAV04 compared with the results from the first breakdown method. The orientation of maximum horizontal stress determined with hydraulic fracturing in KSH04A is also in accordance with the orientation of maximum horizontal stress from KAV01 where the maximum horizontal stress is determined to have an orientation E-W to WNW-ESE.

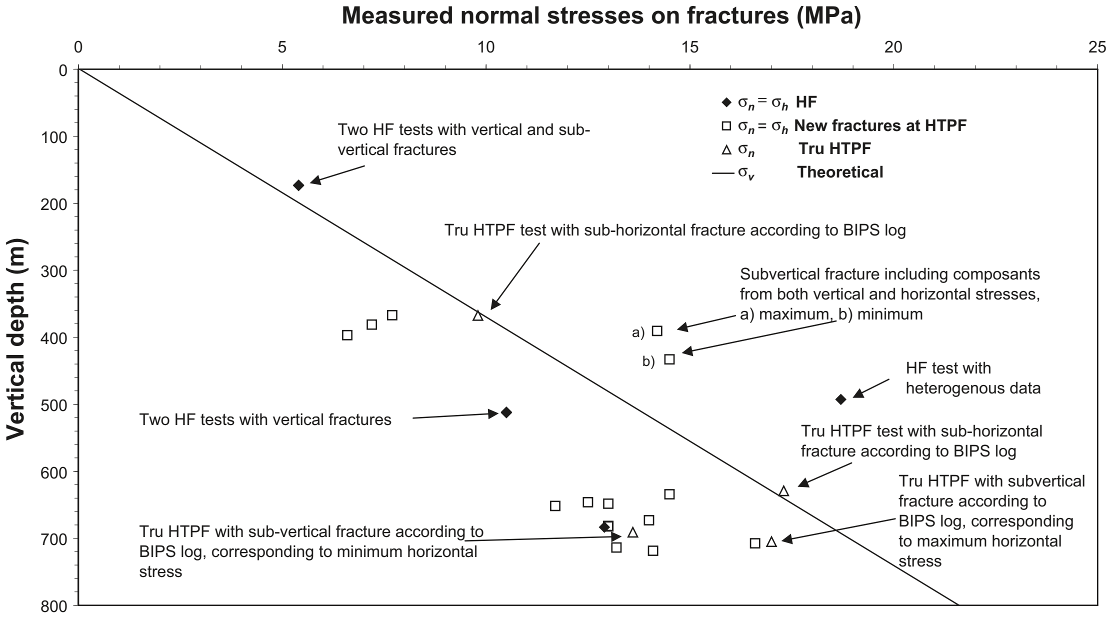


Figure 5-2. *Summary of maximum and minimum horizontal stresses determined with HF and HTPF at borehole KSH01A. Vertical stress is theoretical.*

6 References

Aaltonen J, Gustafsson C, Nilsson P, 2003. Oskarshamn site investigation. RAMAC and BIPS logging and deviation measurements in boreholes KSH01A, KSH01B, and the upper part of KSH02. SKB P-03-73, Svensk Kärnbränslehantering AB.

Ask D, 2001. Inversion and interpretation of hydraulic and overcoring stress measurements in the Äspö region, Sweden. Licentiate thesis, Royal Institute of Technology (KTH), Stockholm, Sweden. ISBN 91-7283-146-4.

Ask H, Morosini M, Samuelsson L E, Stridsman H, 2003. Drilling of cored borehole KSH01. Oskarshamn site investigation. SKB P-03-113, Svensk Kärnbränslehantering AB.

Ask D, 2004. New developments of the integrated stress determination method and application to the Äspö Hard Rock laboratory, Sweden. Doctoral thesis, Royal Institute of Technology (KTH), Stockholm, Sweden. ISBN 91-7283-744-6.

Bredehoeft J D, Wolf R G, Keys W S, Schuter E, 1976. Hydraulic fracturing to determine the regional stress field, Piceance Basin, Colorado. Bull. Geol. Soc. Am 87, pp 250–258.

Cornet F H, 1993. The HTPF method and the integrated stress determination methods. Comprehensive Rock Engineering, vol. 3, (J. Hudson, Ed.). pp. 413–432. Oxford: Pergamon press.

Doe T W, Ingevald K, Strindell L, Leijon B, Hustrulid W, Majer E, Carlsson H, 1983. In-situ stress measurements at the Stripa mine, Sweden. Report LBL-15009, SAC44. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock,

Doe T, Boyce G, Majer E, 1984. Laboratory simulations of hydraulic fracturing stress measurements in salt. Earth Science Division Lawrence Berkely Laboratory University of California.

Enever J, Chopra P N, 1989. Experience with hydraulic fracturing stress measurements in granite. Proceeding International Conference on Rock Stress and Rock Stress Measurements (Stephansson Ed.), Stockholm. Centek Publisher, Luleå, p. 411–420.

Haimson B C, Cornet F H, 2003. ISRM Suggested Methods for rock stress estimation-Part 3: hydraulic fracturing (HF) and/or hydraulic fracturing of pre-existing fractures (HTPF). Int. J. Rock Mech. & Min. Sciences. 40, pp. 1011–1020.

Hubert M K, Willis D G, 1957. Mecahnics of Hydraulic Fracturing. Trans. A.I.M.E (1957), pp. 153–168.

Ito T, Evans K, Kawai K, Hayashi K, 1999. Hydraulic fracturing reopening pressure and the estimation of maximum horizontal stress. Int. J. Rock Mech. & Min. Sciences & Geomech. Abstr. Vol. 36, pp. 811–826.

Klasson H, 1989. Bergspänningsmätningar med hydraulisk spräckning. Master Thesis 1989:100E, Luleå University of Technology (in Swedish).

Lee M Y, Haimson B C, 1989. Statistical Evaluation of Hydraulic Fracturing Stress Measurement Parameters. Int. J. Rock Mech. & Min. Sciences & Geomech. Abstr. Vol. 26, No 6, pp. 447–456.

Ljunggren C, Bjarnason B, 1990. A Comparison of Hydraulic Measuring Techniques for Borehole Rock Stress Measurements. Swedish Rock Engineering Research Foundation. BeFo 211:1/90.

Paris P, Sih G, 1965. Stress analysis of a crack. In Fracture Toughness and its testing. American Society of testing and materials Special Publications 381, pp. 30–83.

Rutqvist J, 1995. Coupled stress-flow properties of rock joints from hydraulic field testing. Doctoral Thesis, Royal Institution of Technology, Stockholm

Rutqvist J, Tsang C-F, Stephansson O, 2000. Uncertainty in the principal stress estimation from hydraulic fracturing measurements due to the presence of the induced fracture. Int. J. Rock Mech. & Min. Sciences & Geomech. Abstr. Vol. 37, pp. 107–120.

Sjöberg J, 2004. Overcoring rock stress measurements in borehole KAV04. Oskarshamn site investigation. SKB P-04-84, Svensk Kärnbränslehantering AB.

SKB, 2004. Preliminary site description. Simpevarp area – version 1.1. SKB R-04-25, Svensk Kärnbränslehantering AB.

Tarantola A, Valette B, 1982. Generalized Nonlinear Inverse Problem Solved Using the Least Squares Criterion. Rev. Geophys. Space. Phys. 20, pp. 219–232.

Wallroth T, 1991. Hydraulically induced failures and international HDR activities. Chalmers University of Technology, Göteborg, Sweden. ISSN 1101–055x. Publ. Fj-11.

Appendix A

Results from HF tests

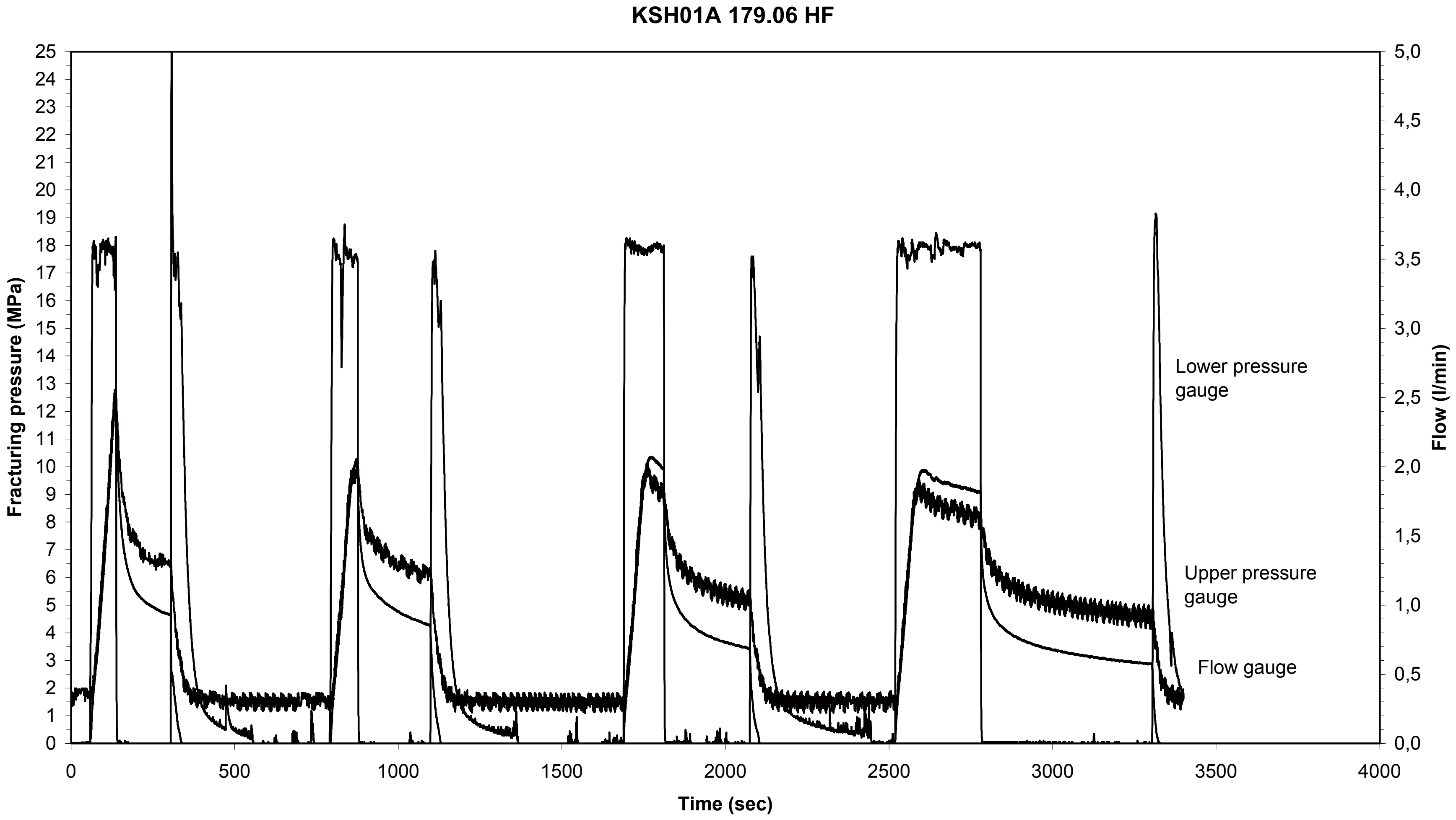


Figure A1. *Pressure and flow record during Hydraulic fracturing at 179.06 m borehole length.*

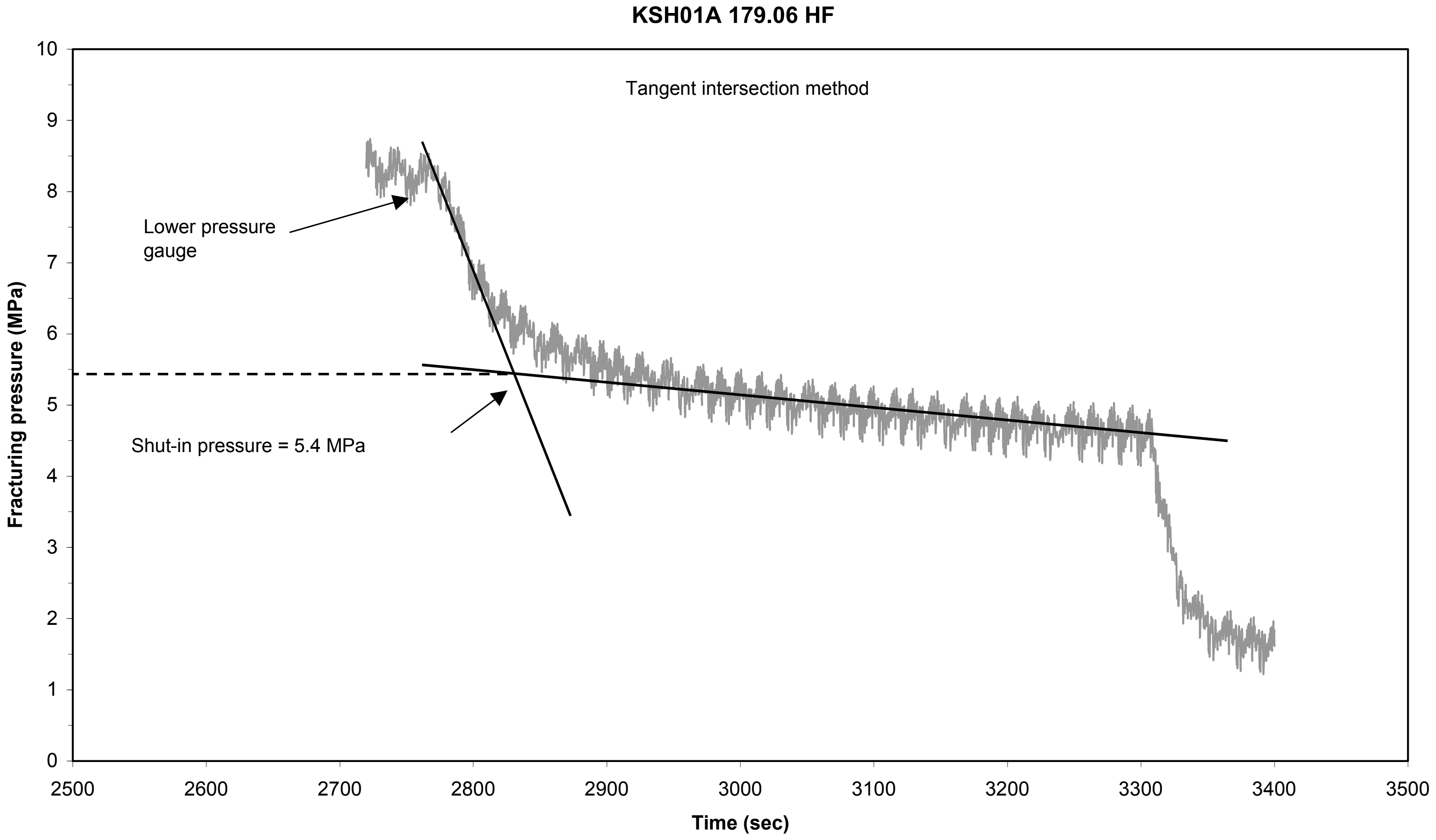


Figure A2. *Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at 179.06 m borehole length.*

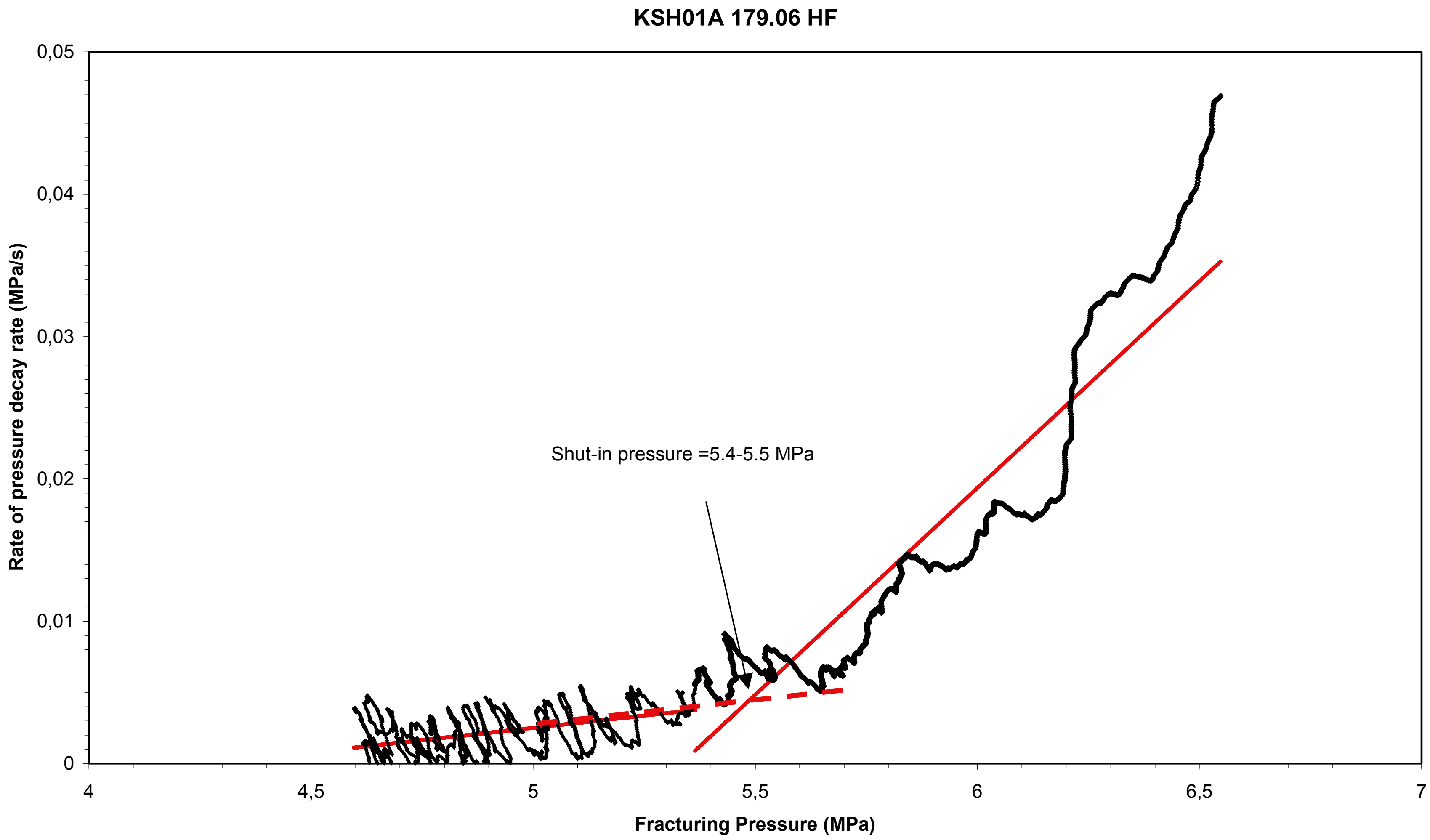


Figure A3. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 179.06 m borehole length.*

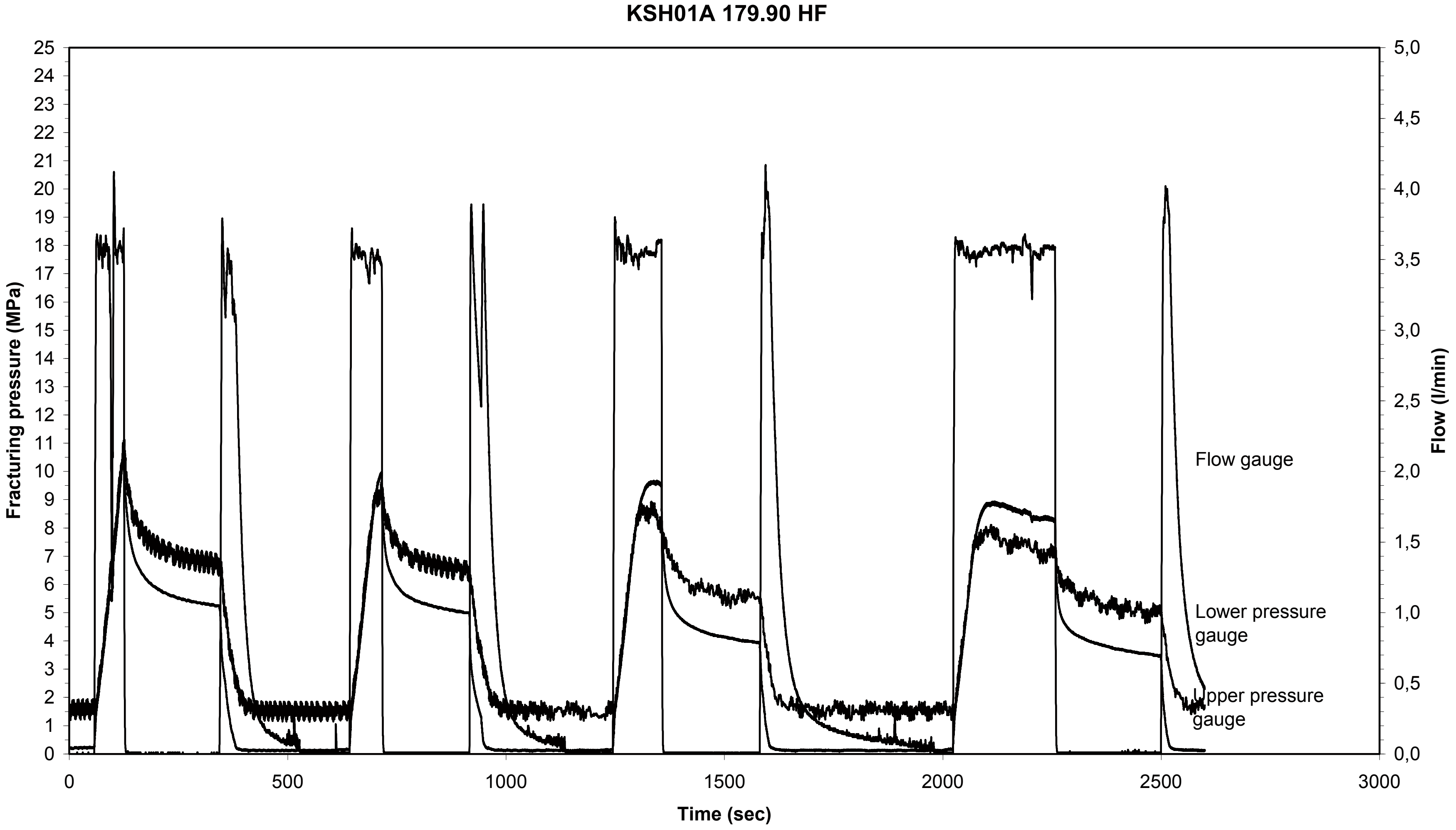


Figure A4. *Pressure and flow record during Hydraulic fracturing at 179.90 m borehole length.*

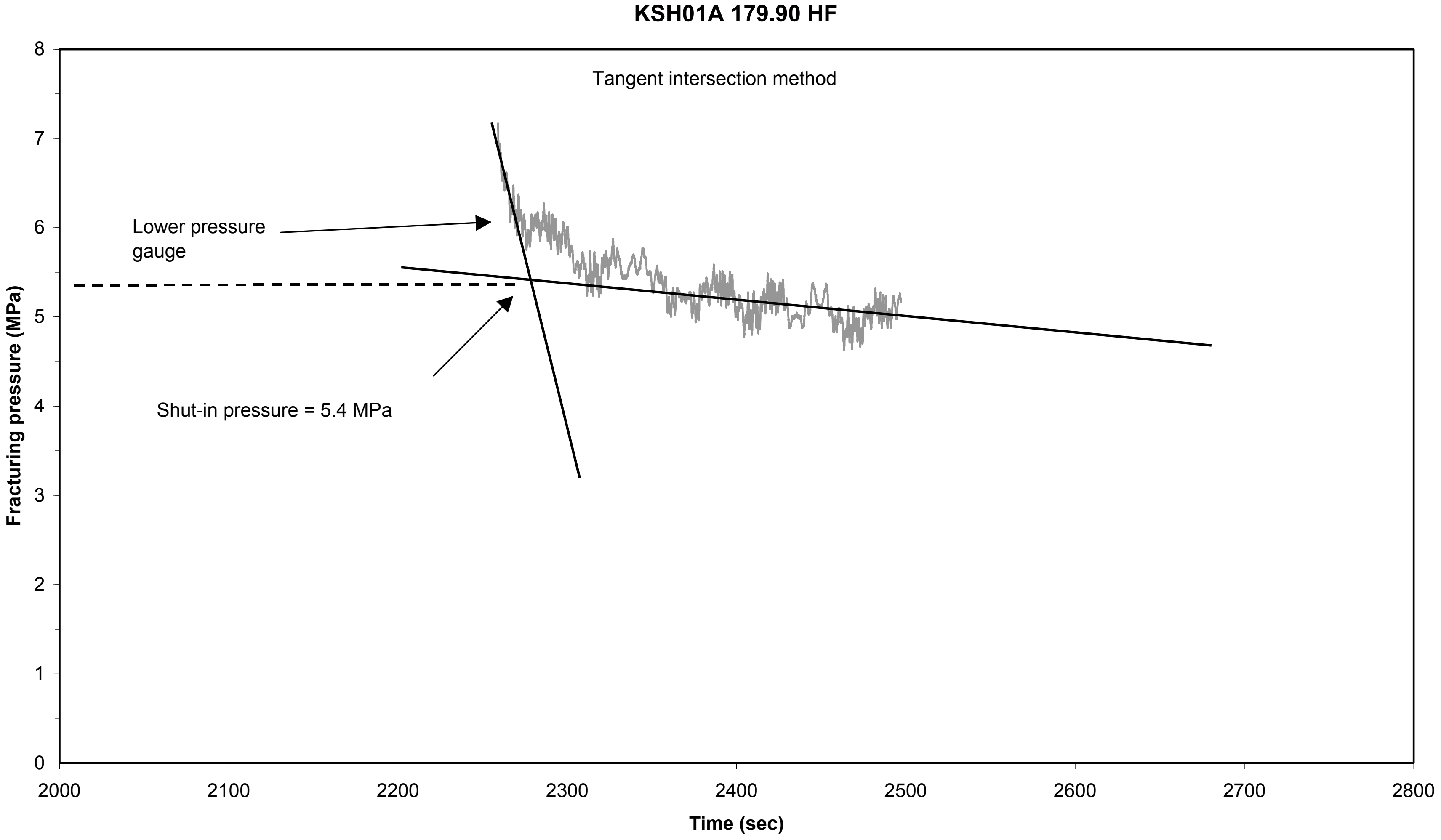


***Figure A5**. Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at 179.90 m borehole length.*

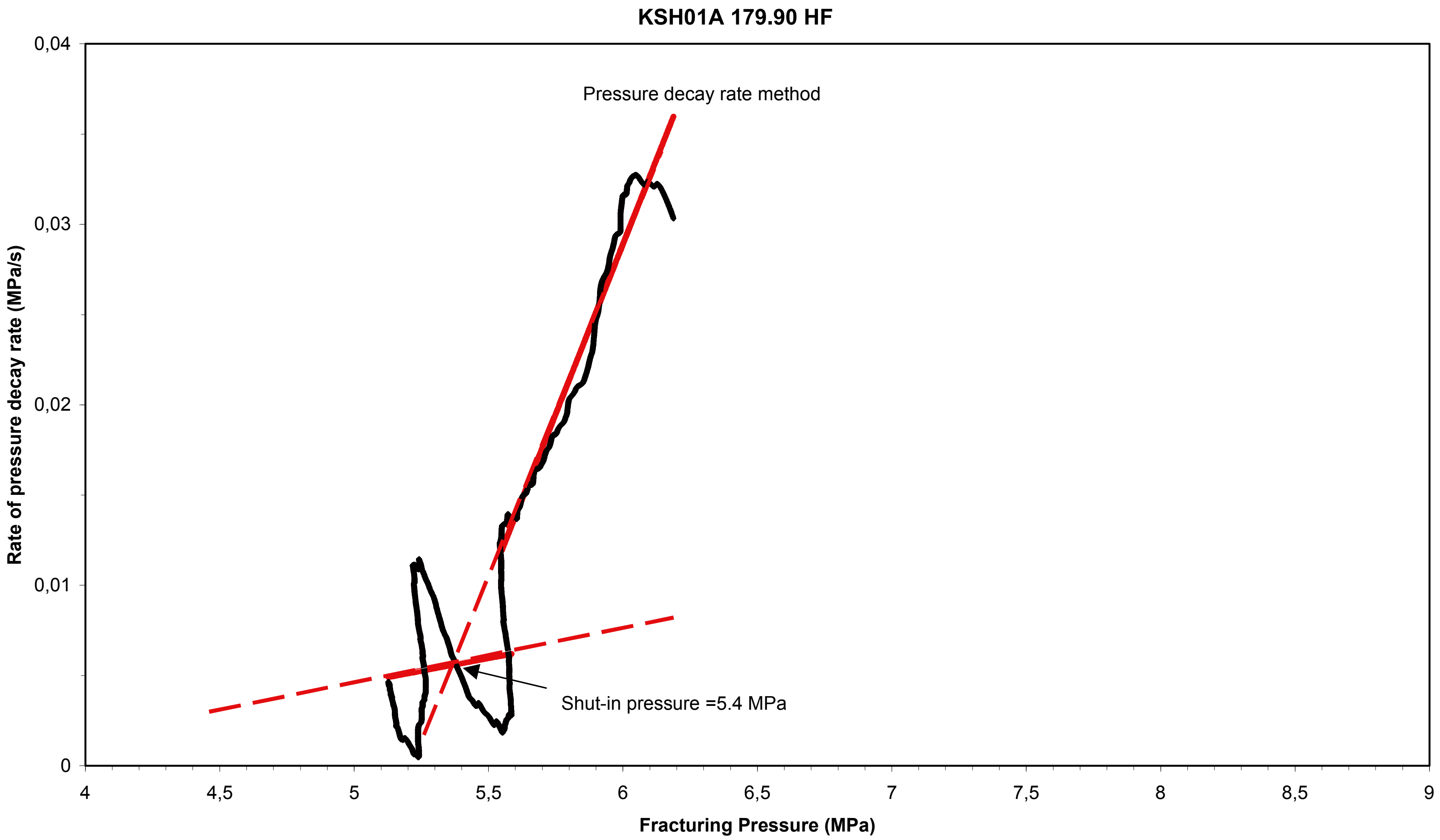


Figure A6. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 179.90 m borehole length.*

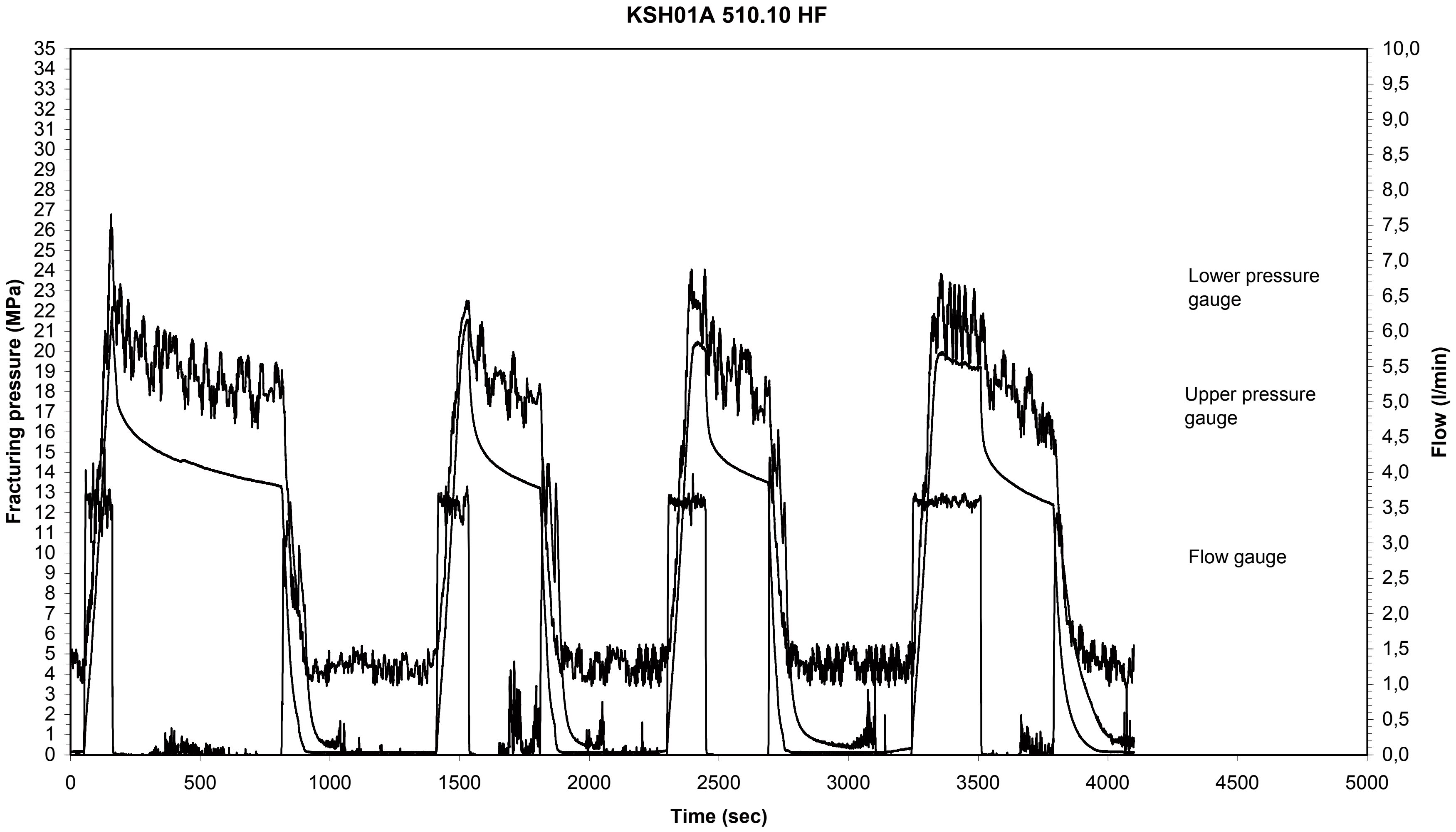


Figure A7. *Pressure and flow record during Hydraulic fracturing at 510.10 m borehole length.*

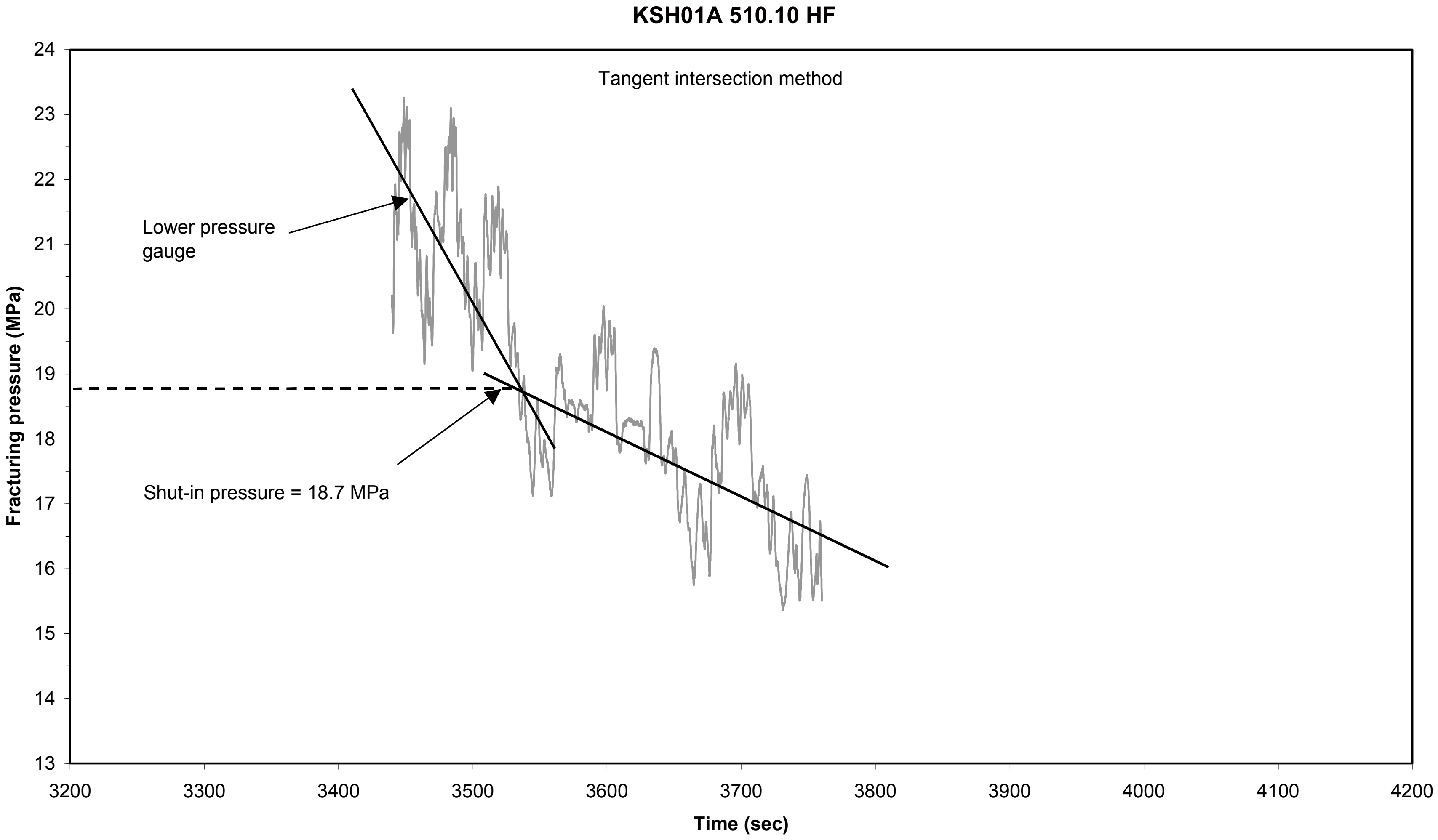


***Figure A8**. Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at 510.10 m borehole length.*

N/A

The raw data set became too saw-tooth shaped to be able to use in the analysis.

Figure A9. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 510.10 m borehole length.*

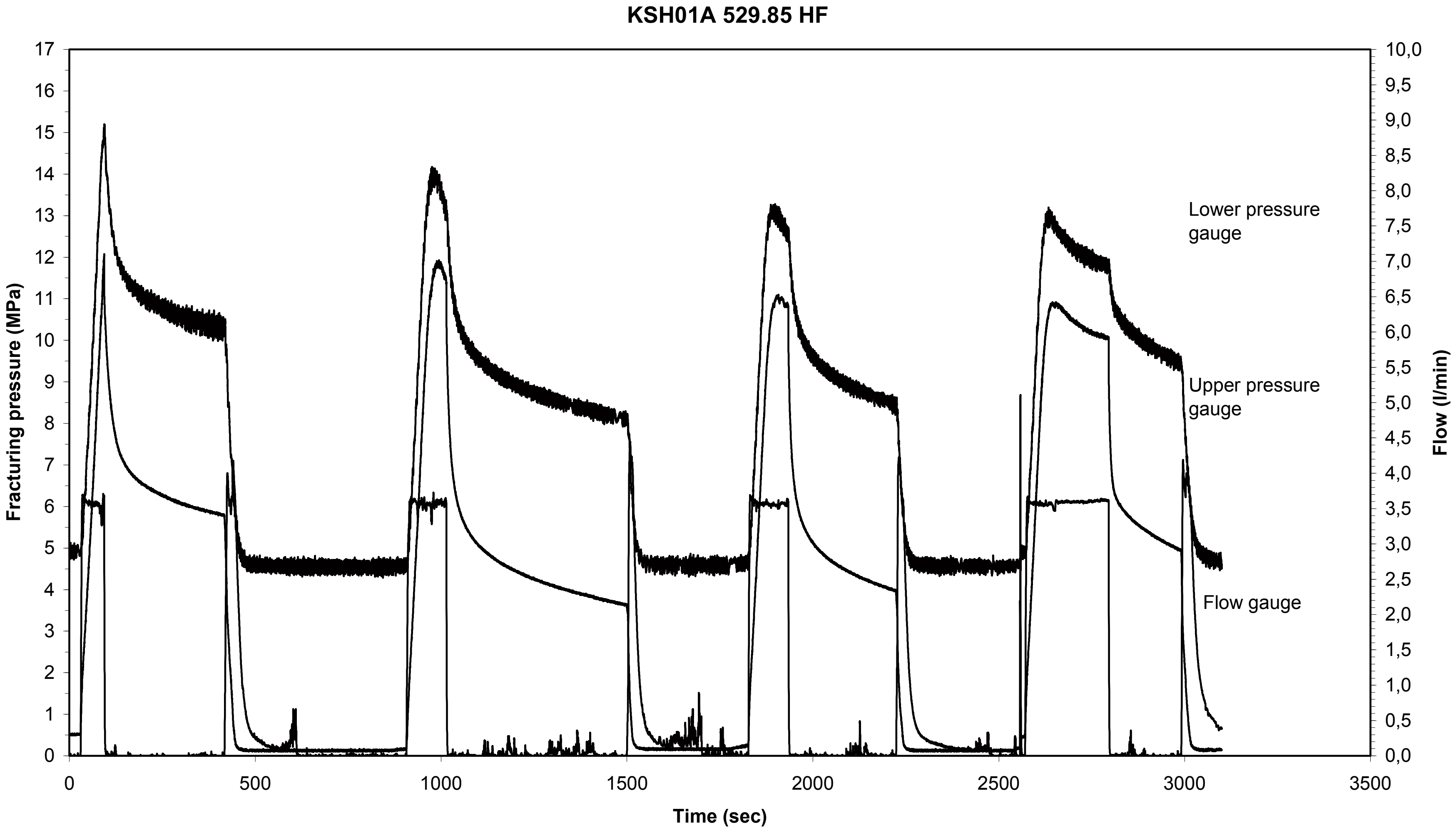


Figure A10. *Pressure and flow record during Hydraulic fracturing at 529.85 m borehole length.*

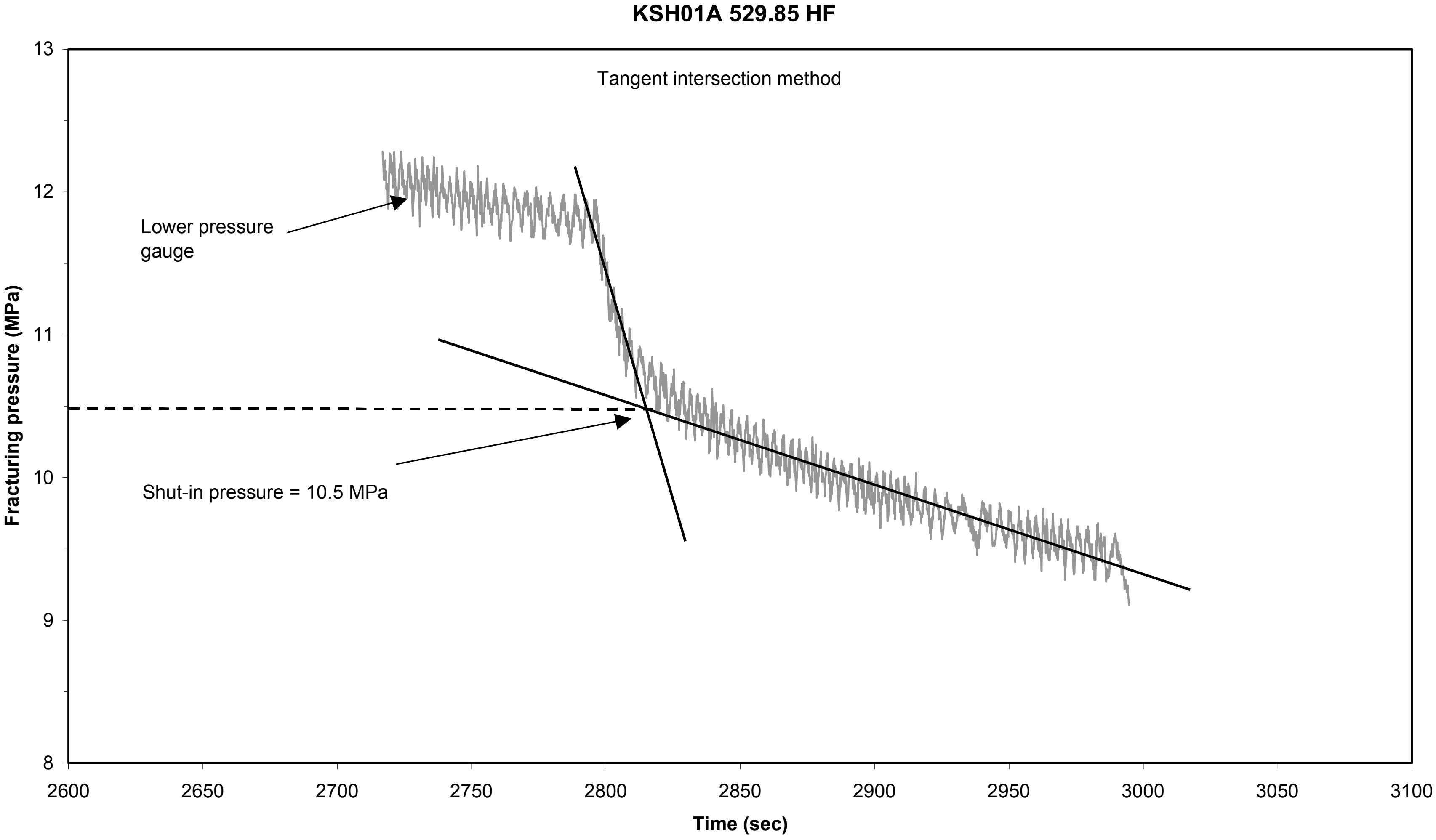


Figure A11. *Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at 529.85 m borehole length.*

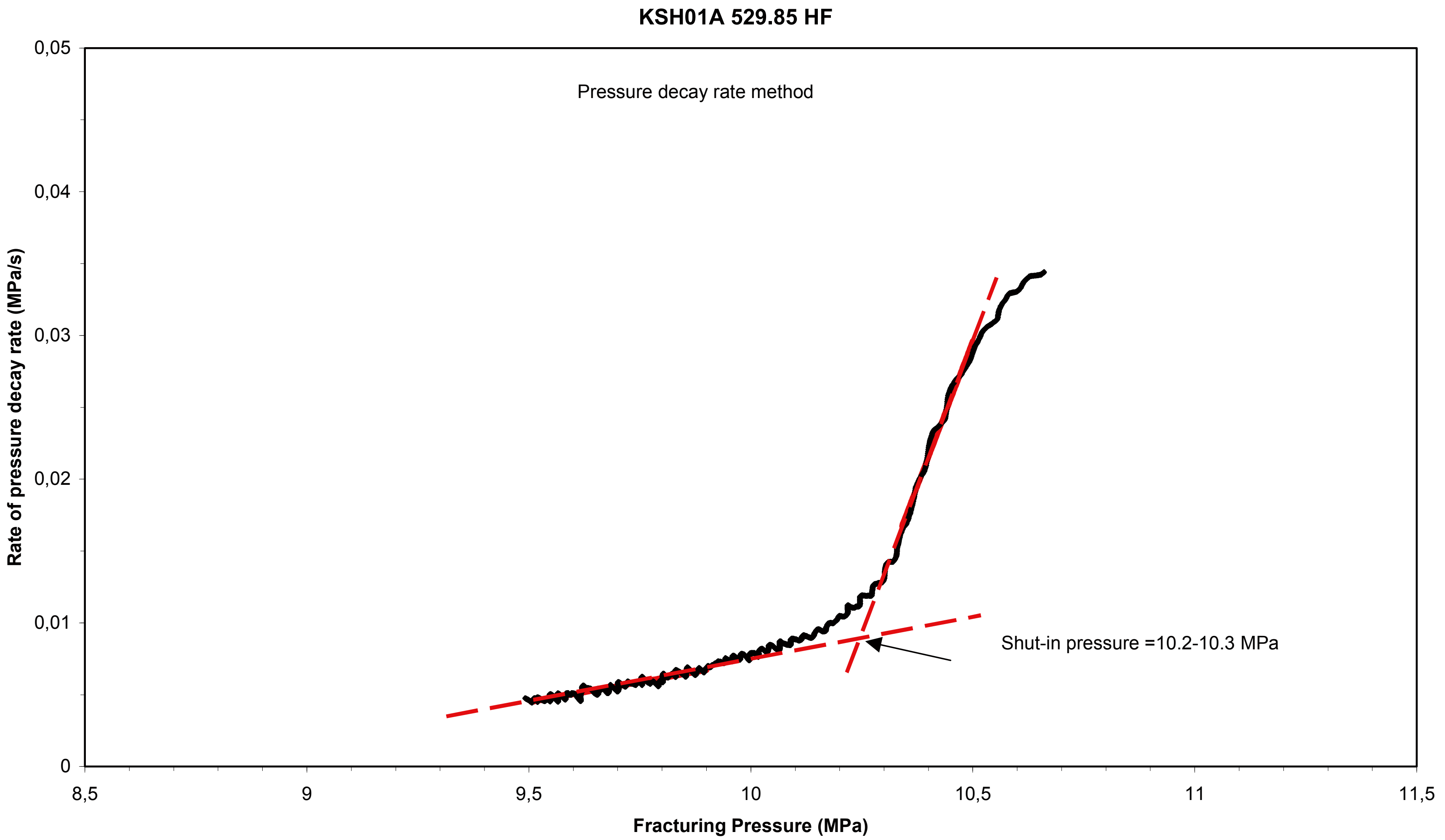


Figure A12. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 529.85 m borehole length.*

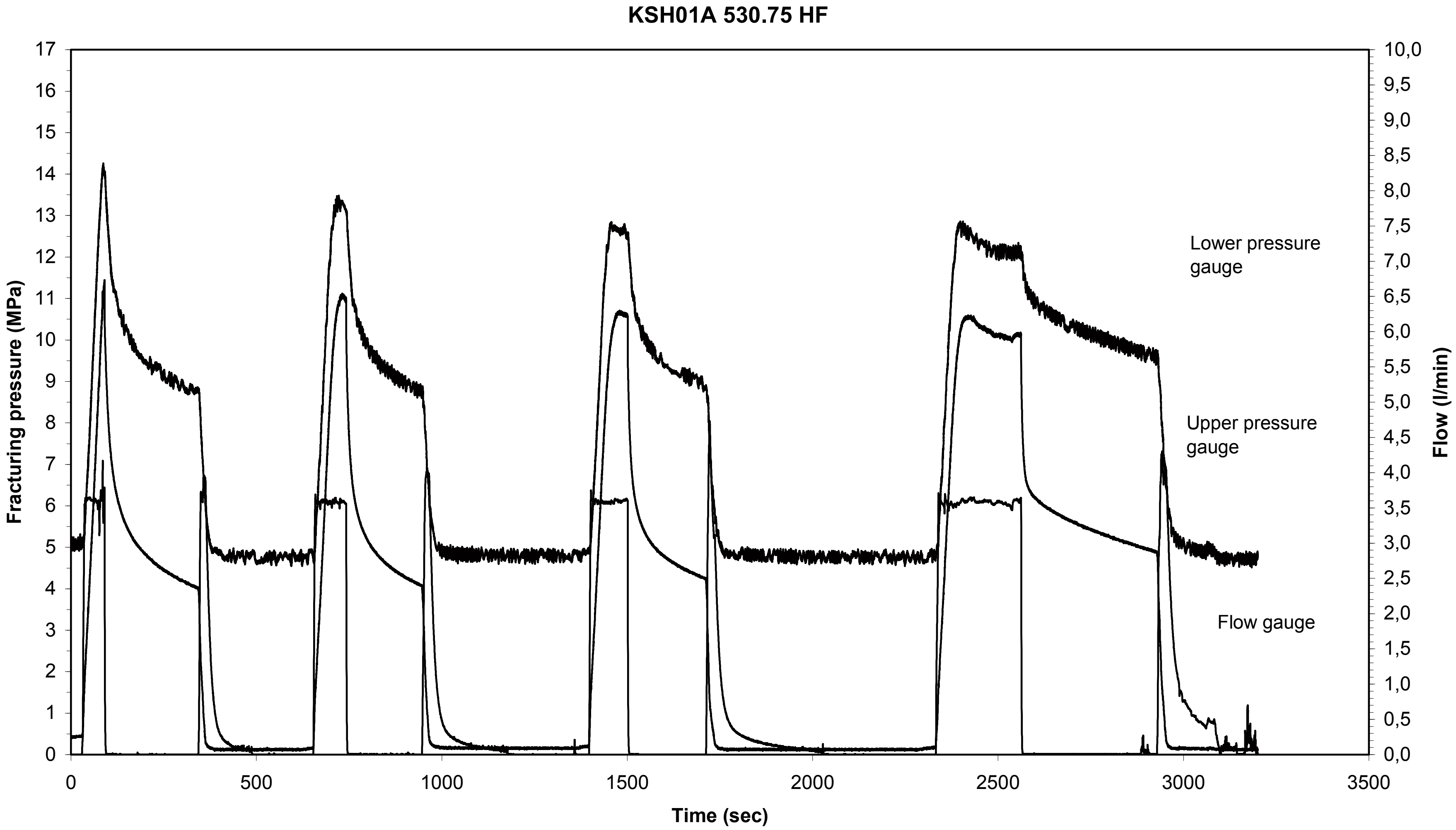


Figure A13. *Pressure and flow record during Hydraulic fracturing at 530.75 m borehole length.*

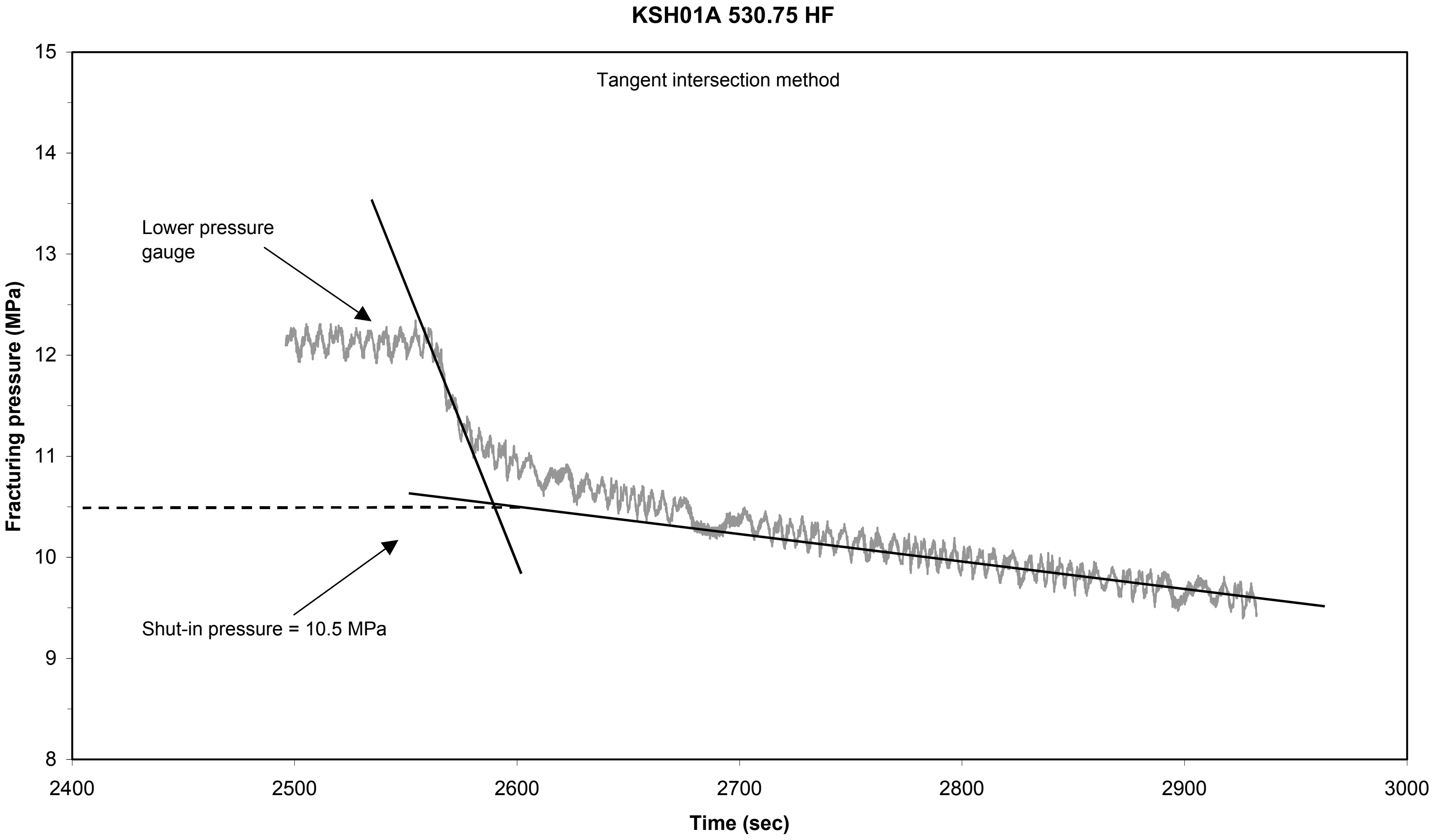


Figure A14. *Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at 530.75 m borehole length.*

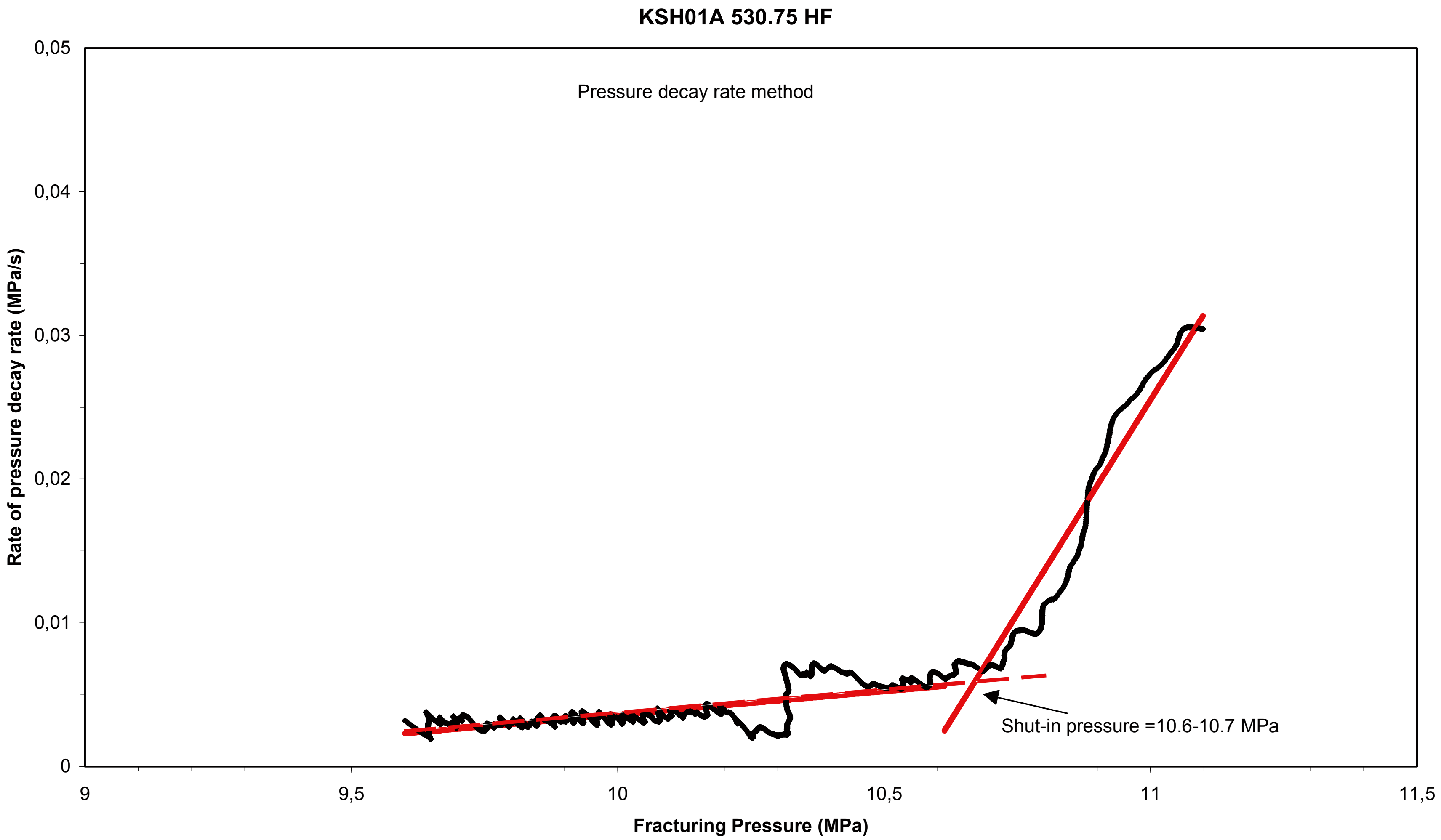


Figure A15. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 530.75 m borehole length.*

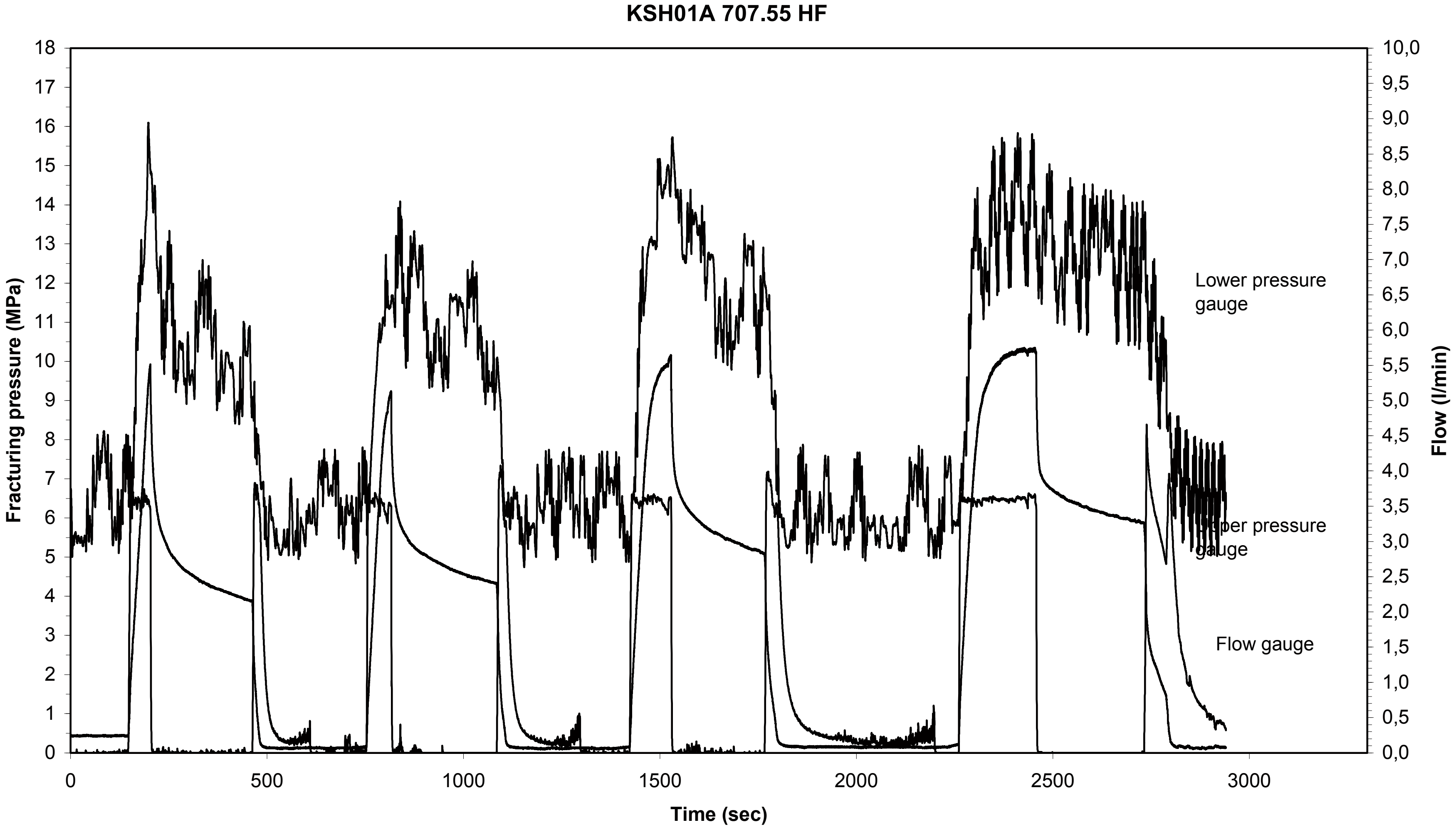


Figure A16. *Pressure and flow record during Hydraulic fracturing at 707.55 m borehole length.*

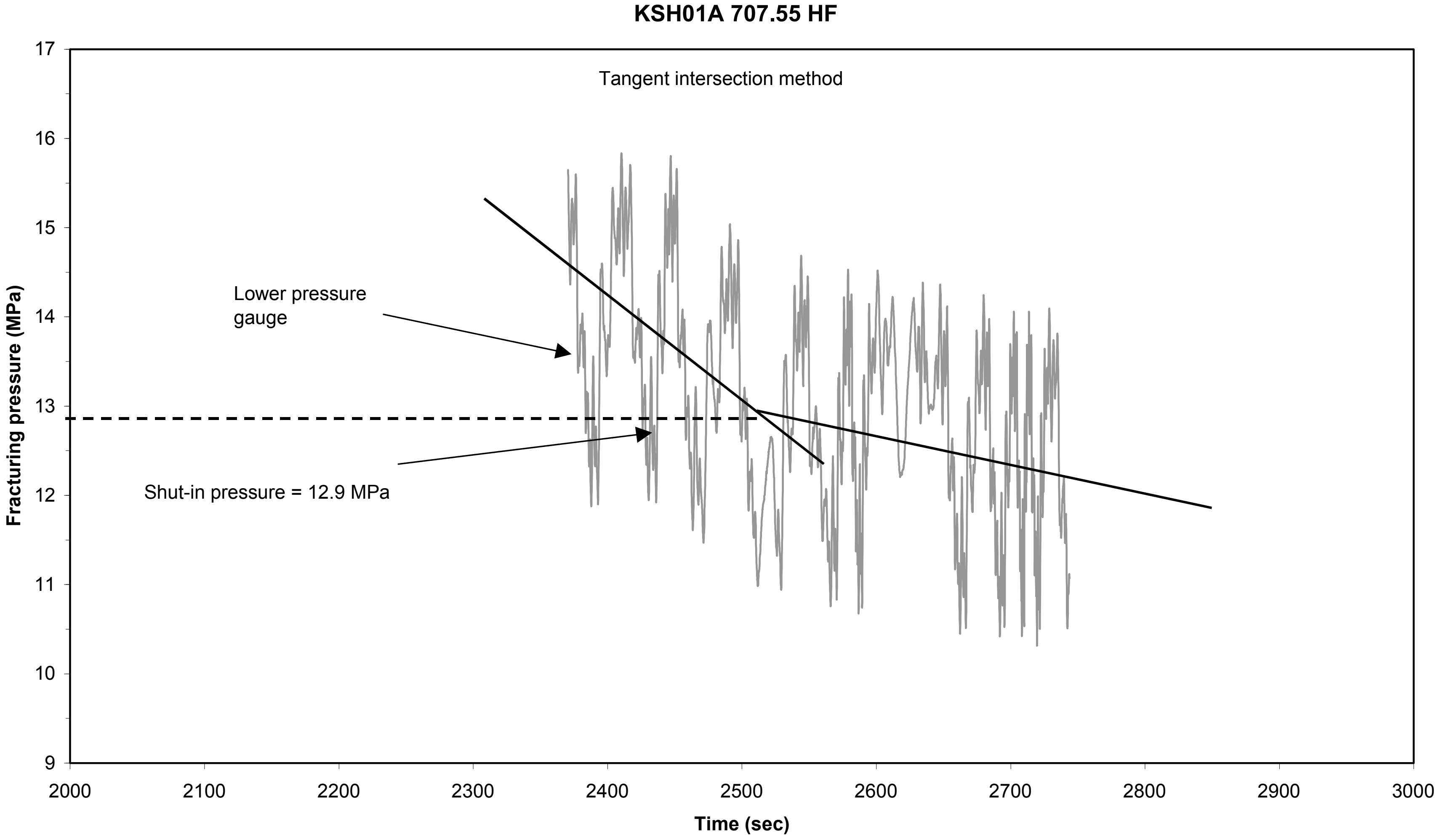


Figure A17. *Shut-in pressure determined with tangent intersection method from Hydraulic fracturing at level 707.55 m.*

N/A

The raw data set became too saw-tooth shaped to be able to use in the analysis.

Figure A18. *Shut-in pressure determined by the decay rate method from Hydraulic fracturing at 707.55 m borehole length.*

Appendix B

Results from HTPF tests

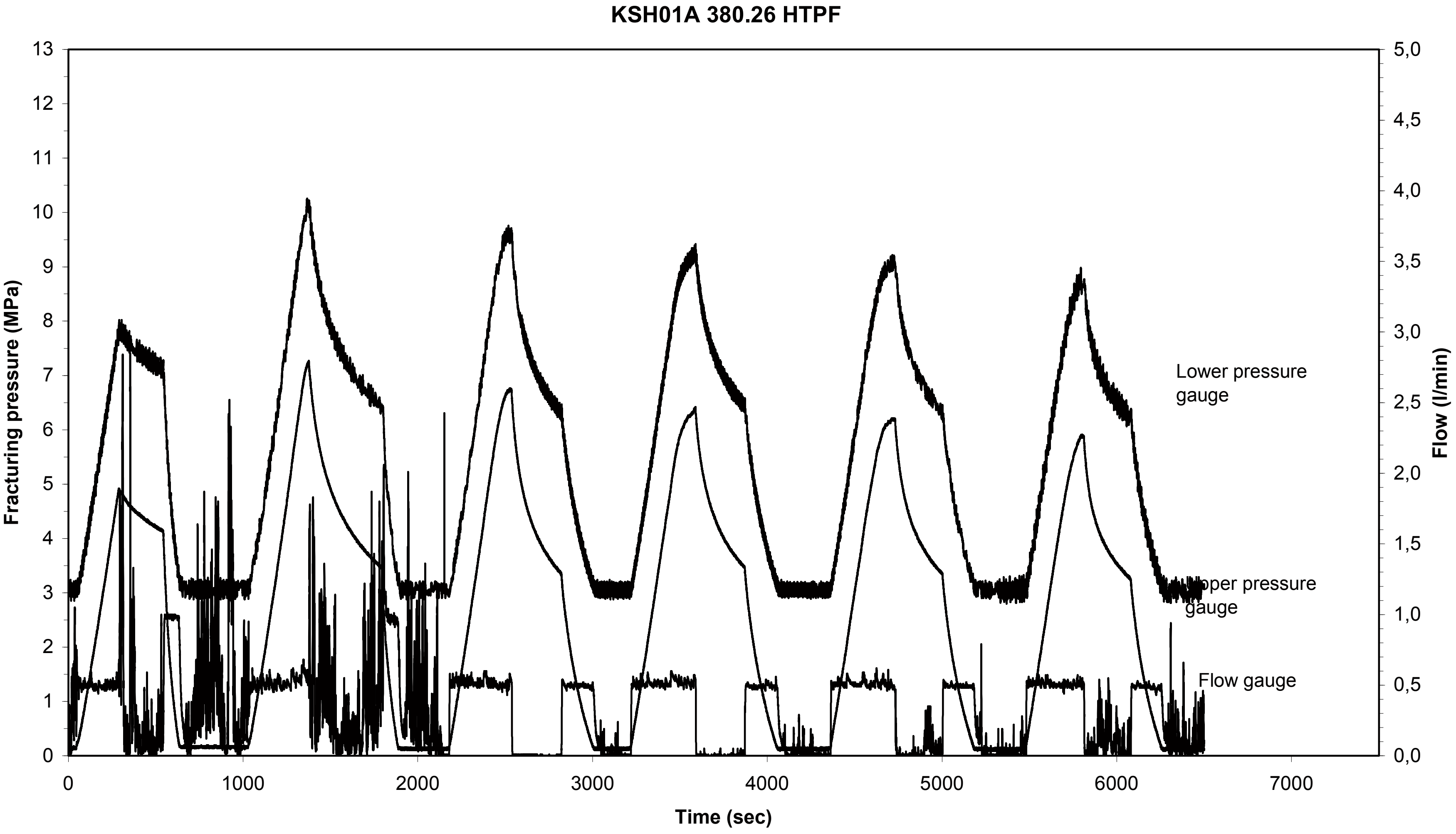


Figure B1. *Pressure and flow record during HTPF tests at 380.26 m borehole length.*

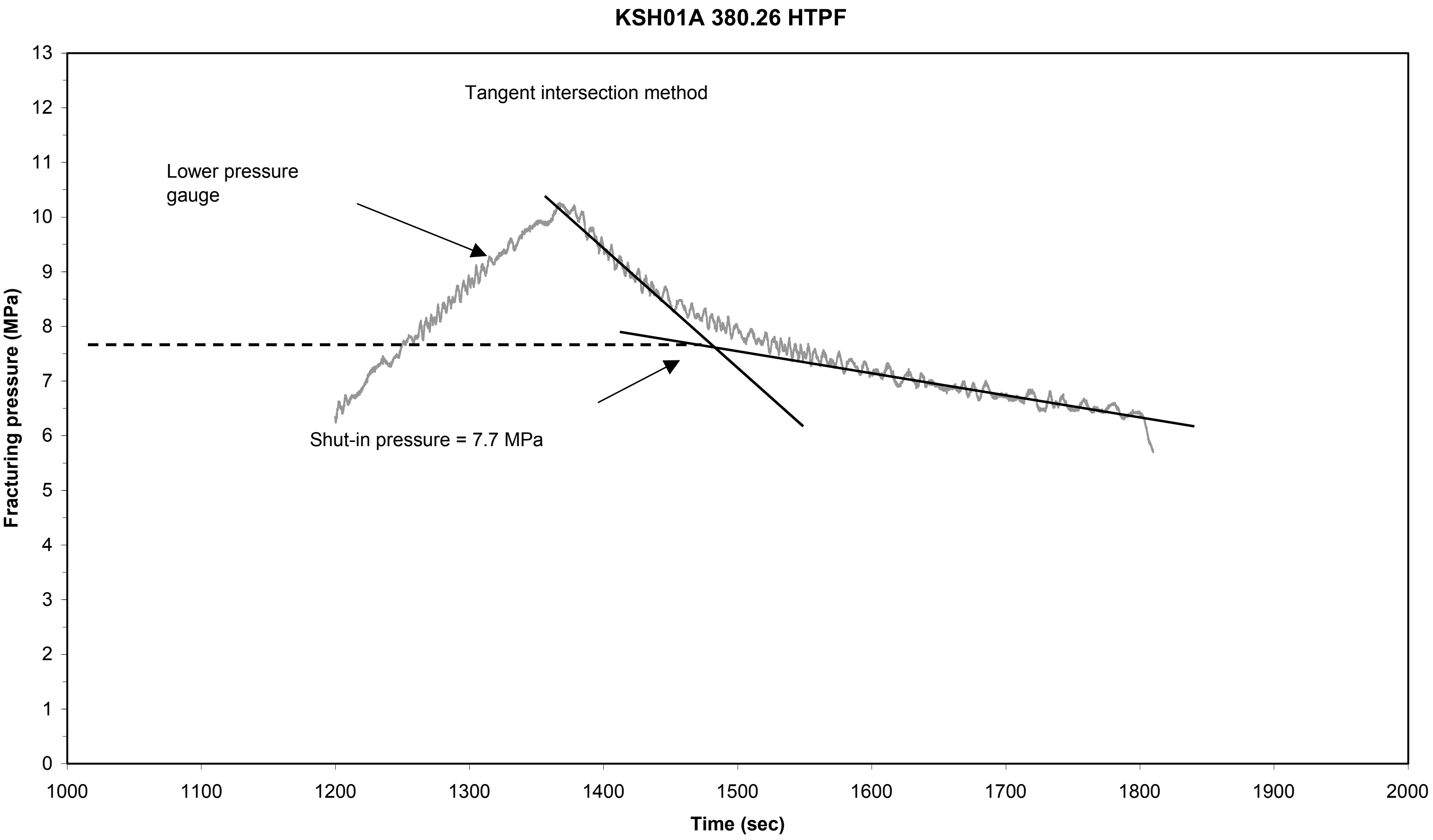


Figure B2. *Shut-in pressure determined with tangent intersection method from HTPF at 380.26 m borehole length.*

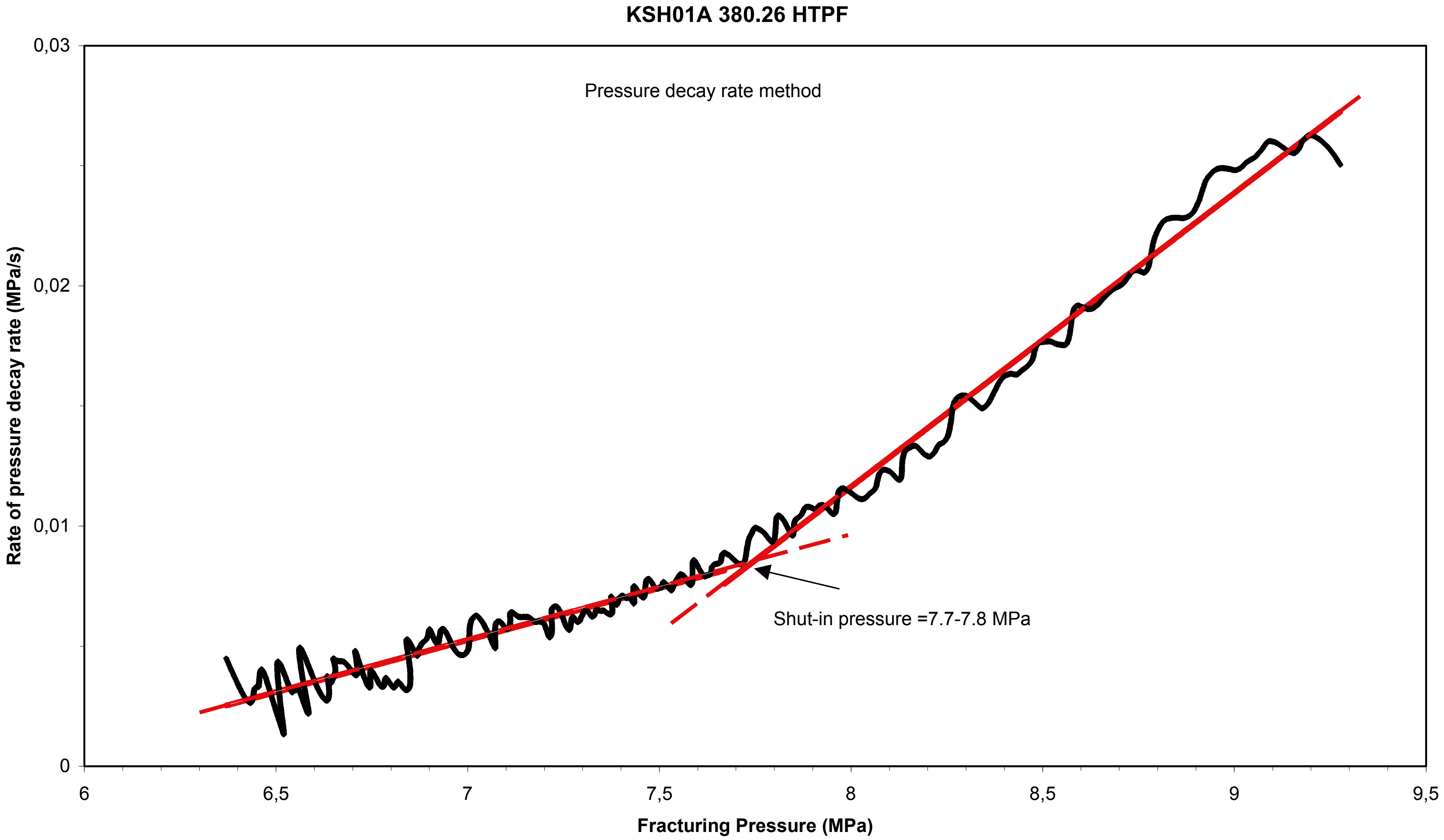


Figure B3. *Shut-in pressure determined by the decay rate method from HTPF at 380.26 m borehole length.*

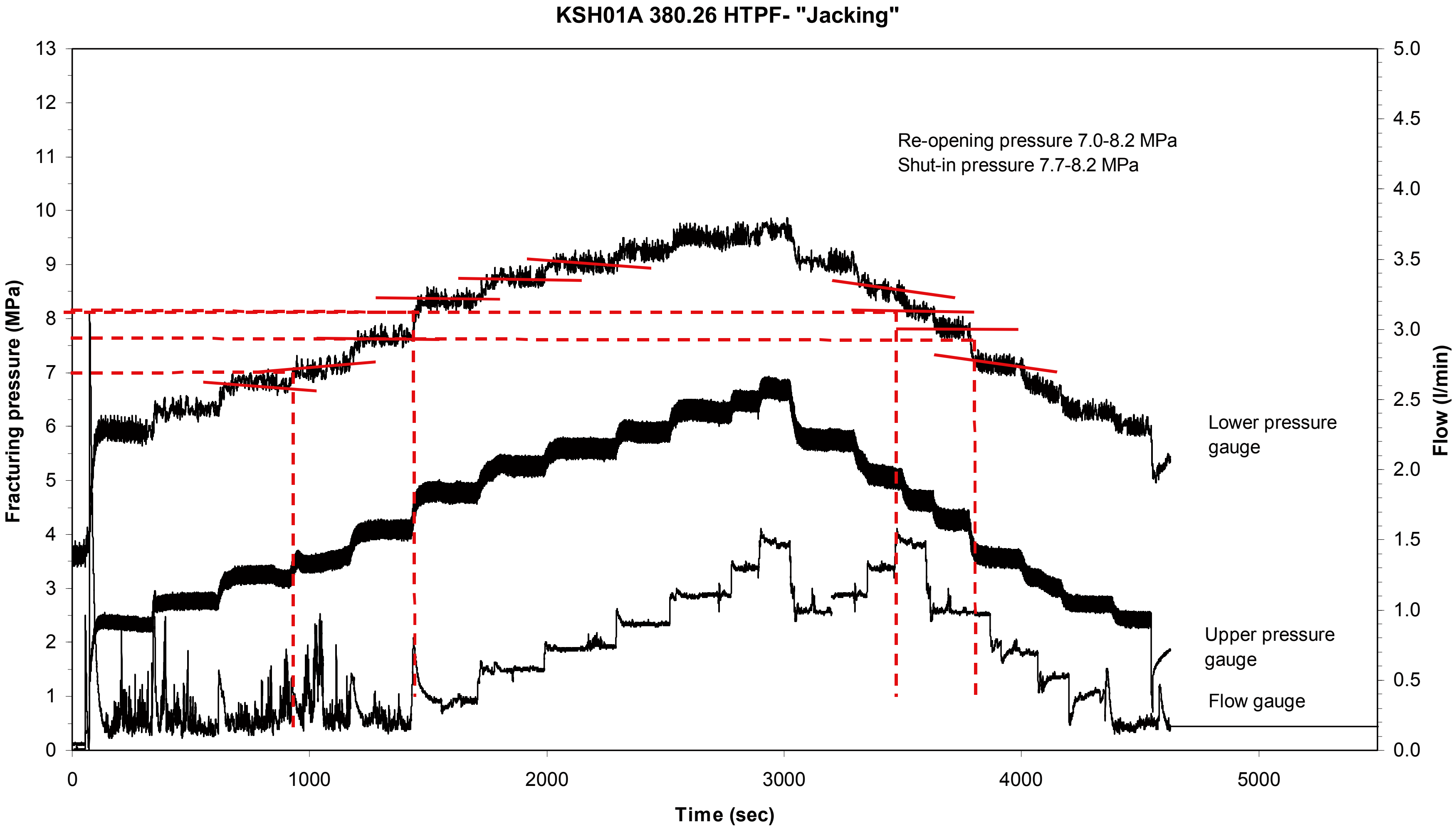


Figure B4. *Shut-in pressure determined from jacking test (HTPF) at 380.26 m borehole length.*

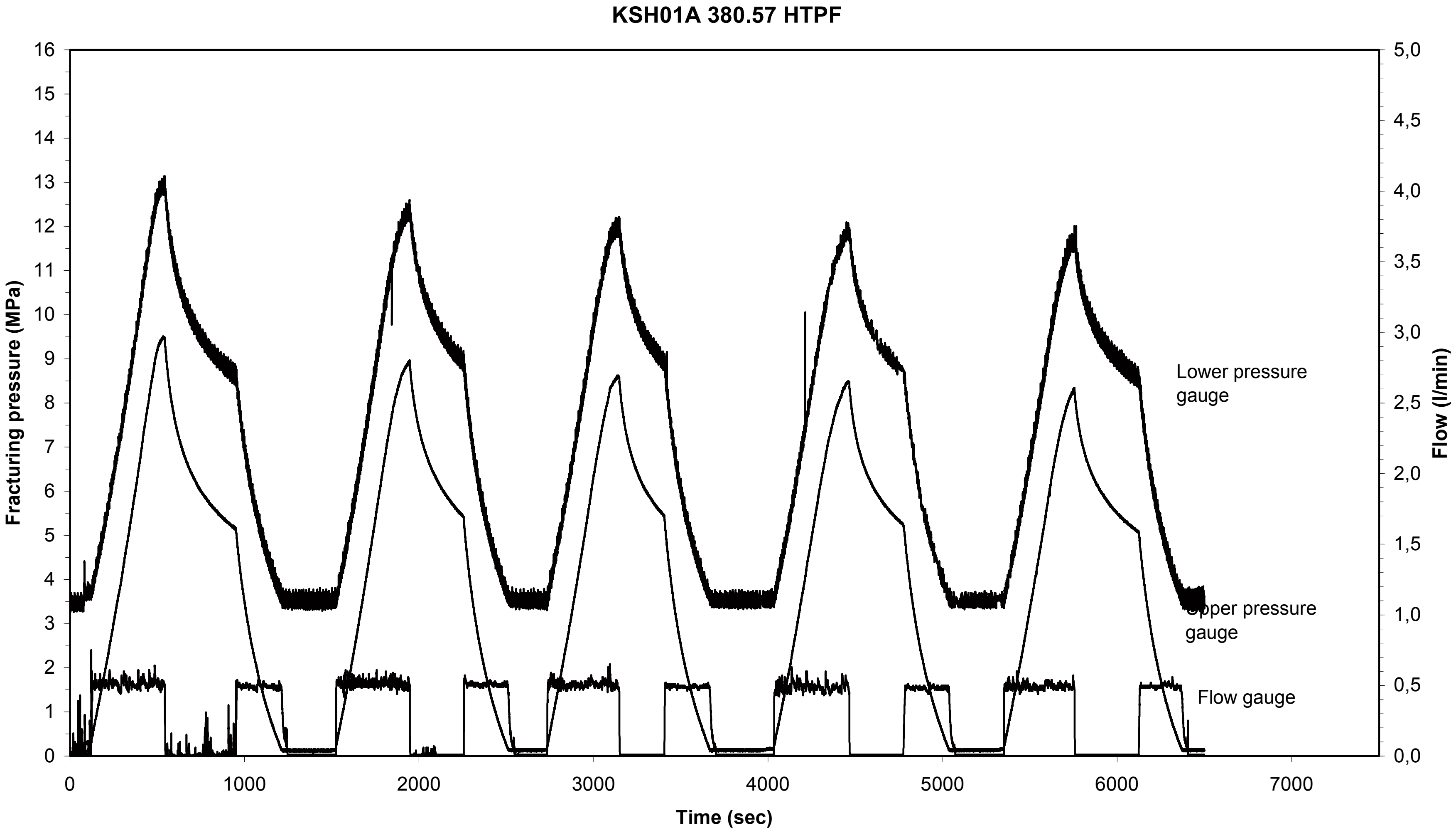


Figure B5. *Pressure and flow record during HTPF tests at 380.57 m borehole length.*

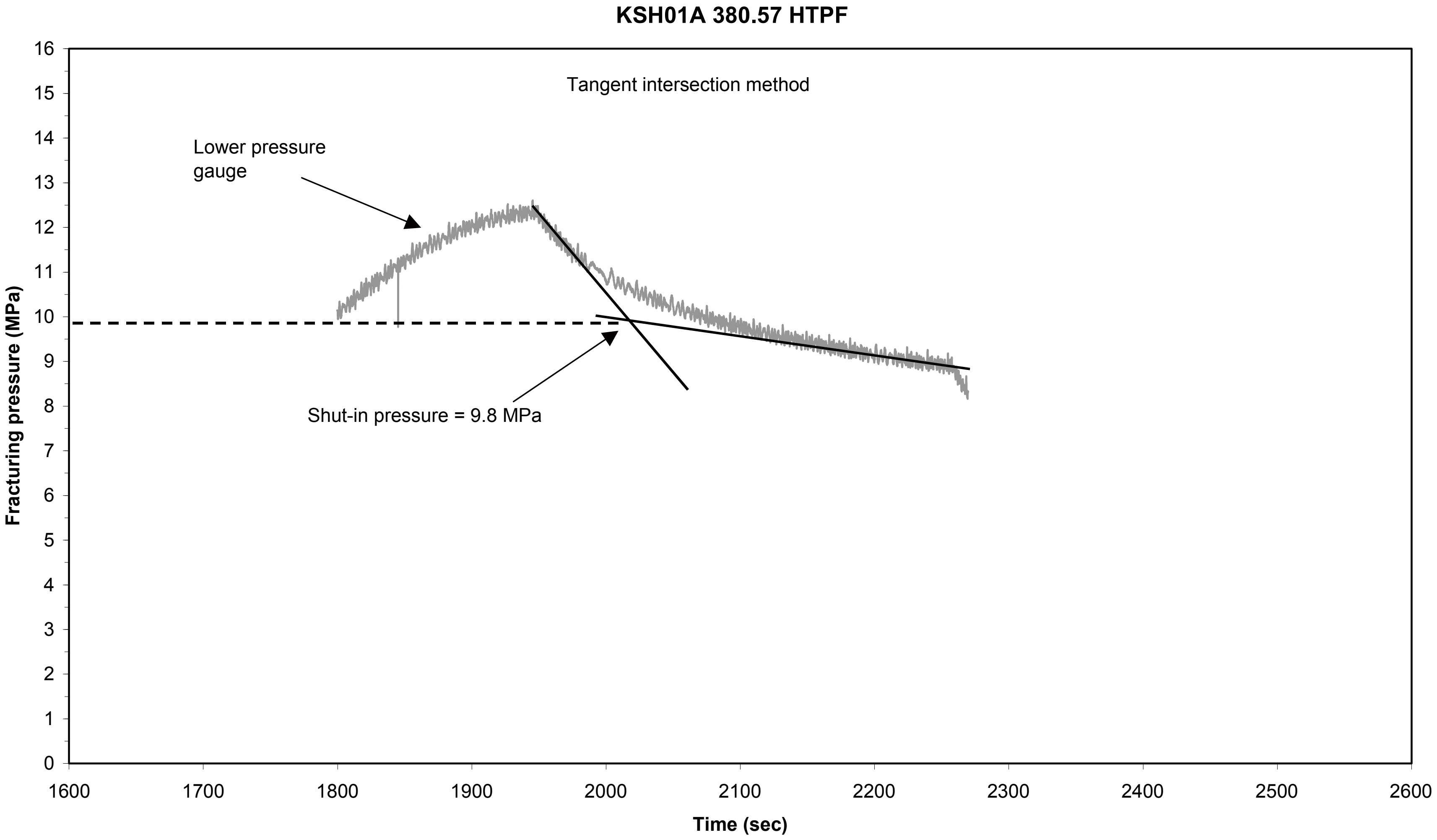


Figure B6. *Shut-in pressure determined with tangent intersection method from HTPF at 380.57 m borehole length.*

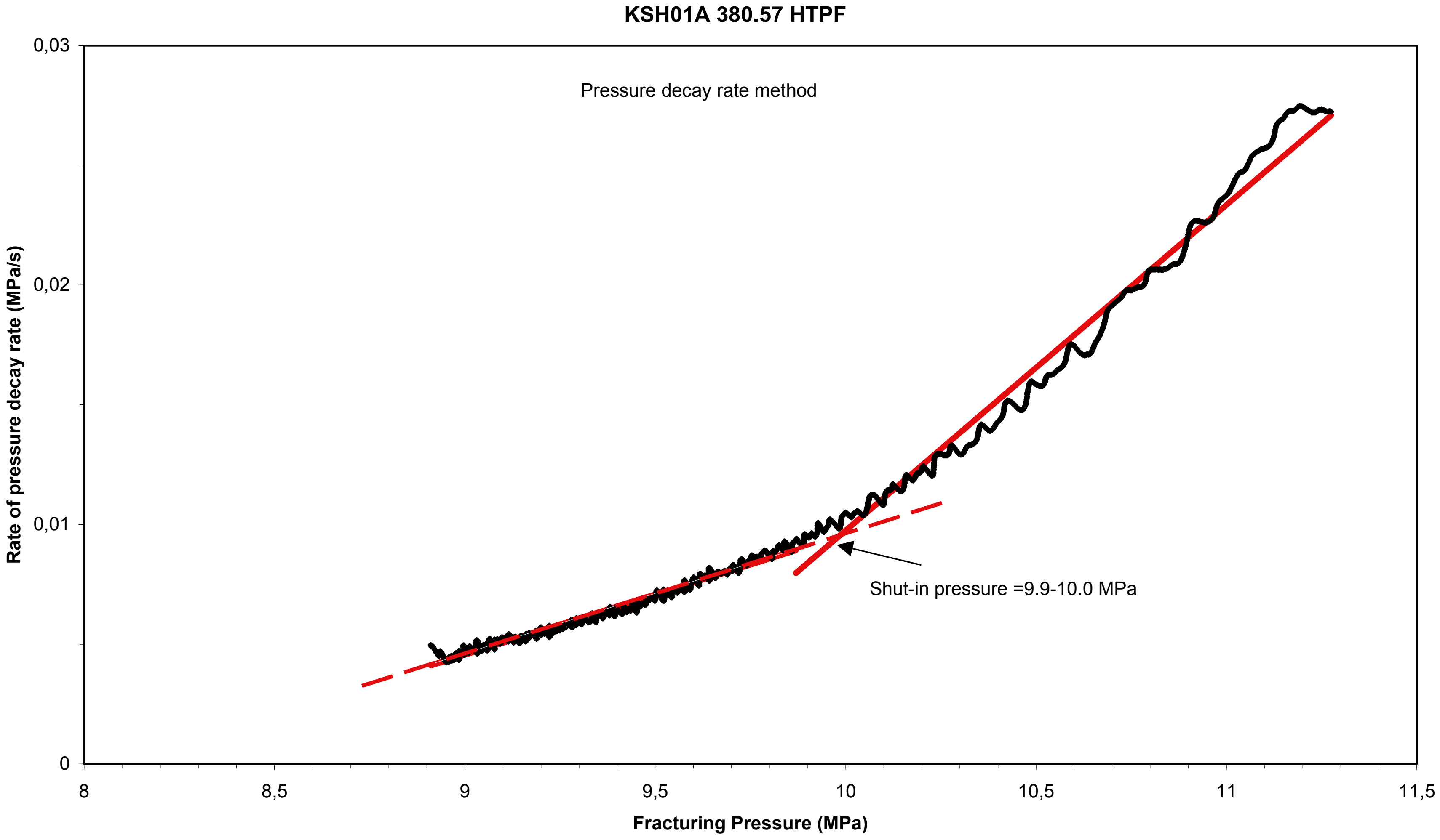


Figure B7. *Shut-in pressure determined by the decay rate method from HTPF at 380.57 m borehole length.*

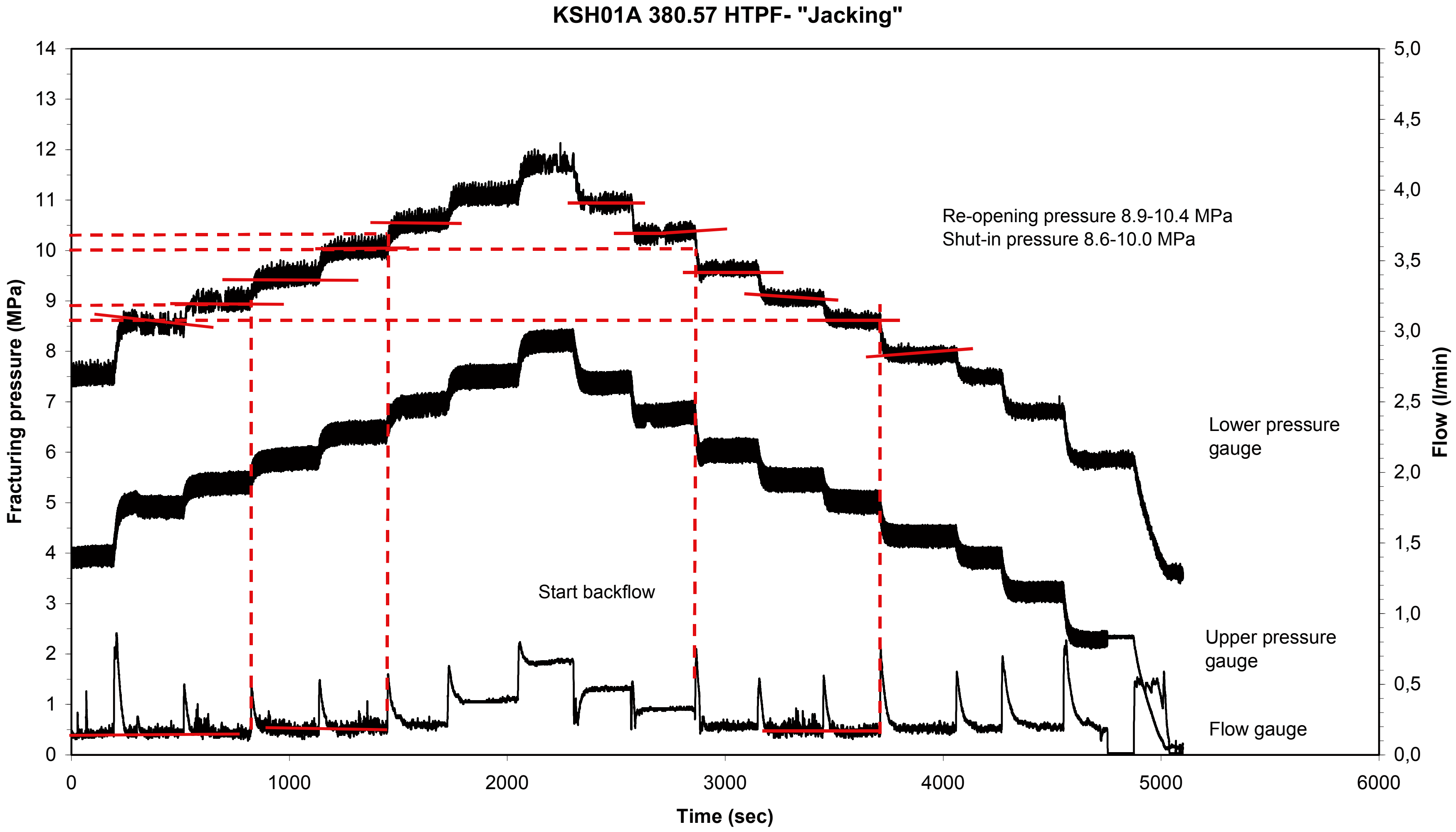


Figure B8. *Shut-in pressure determined from jacking test (HTPF) at 380.57 m borehole length.*

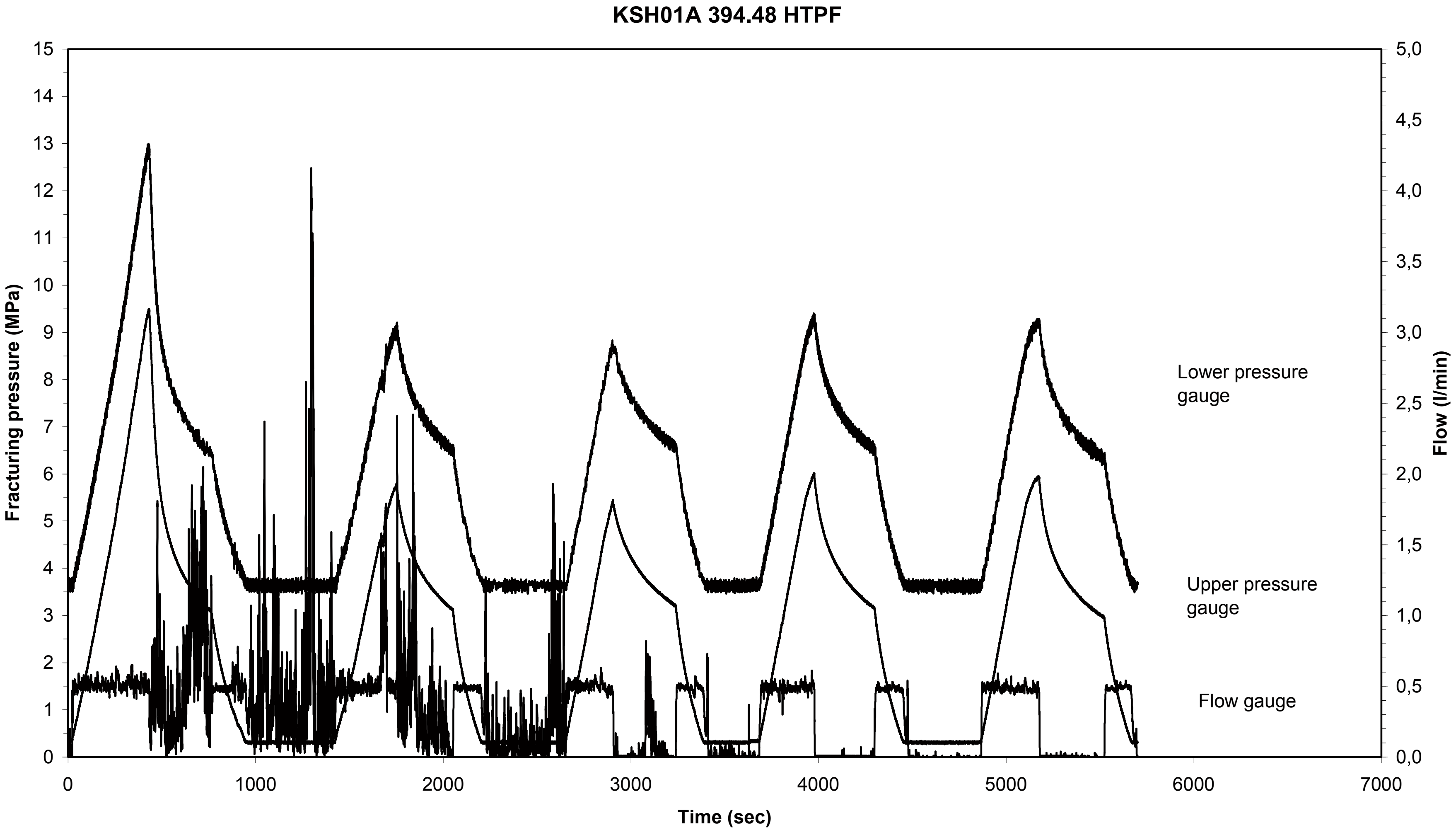


Figure B9. Pressure and flow record during HTPF tests at 394.48 m borehole length.

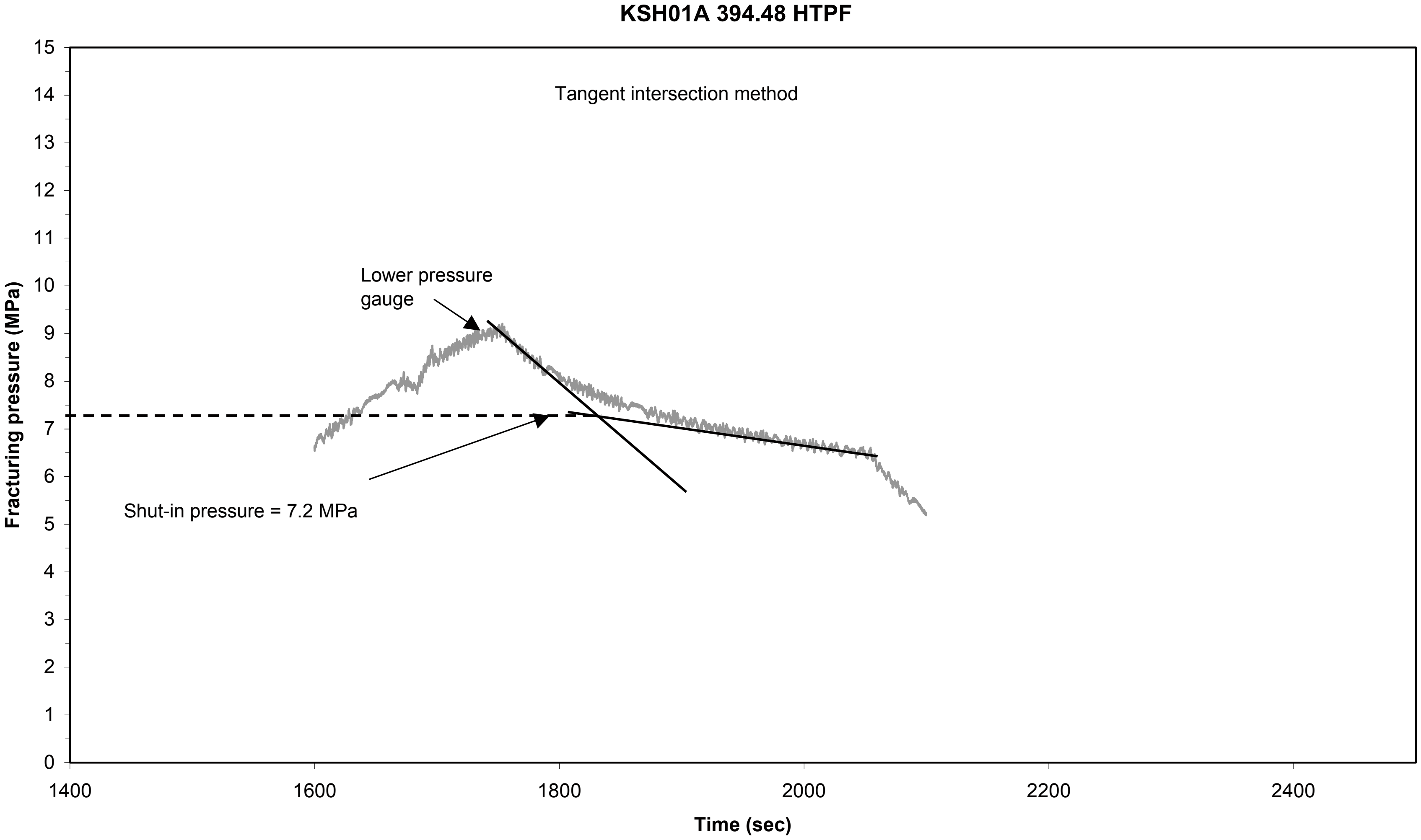


Figure B10. *Shut-in pressure determined with tangent intersection method from HTPF at 394.48 m borehole length.*

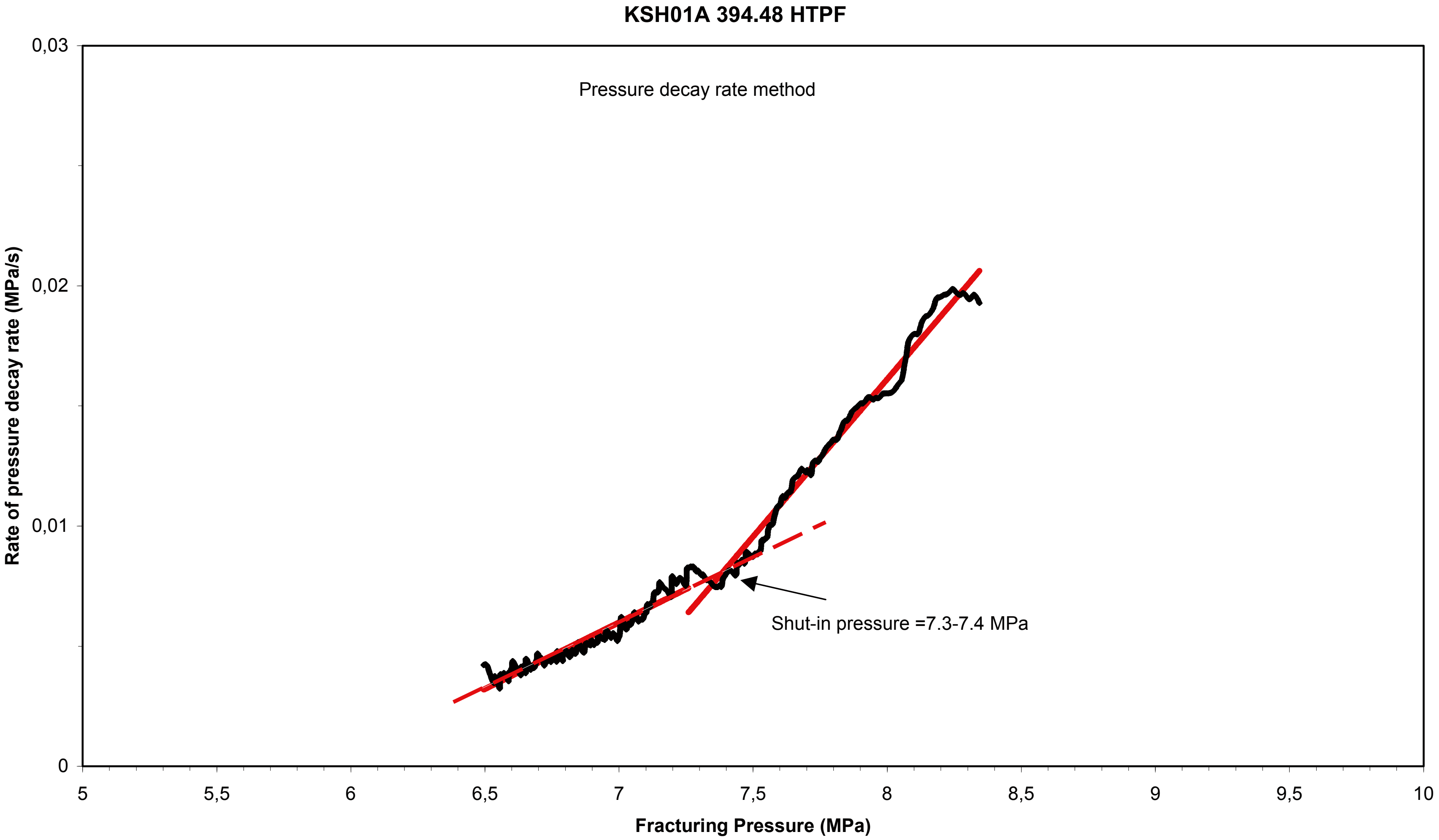


Figure B11. *Shut-in pressure determined by the decay rate method from HTPF at 394.48 m borehole length.*

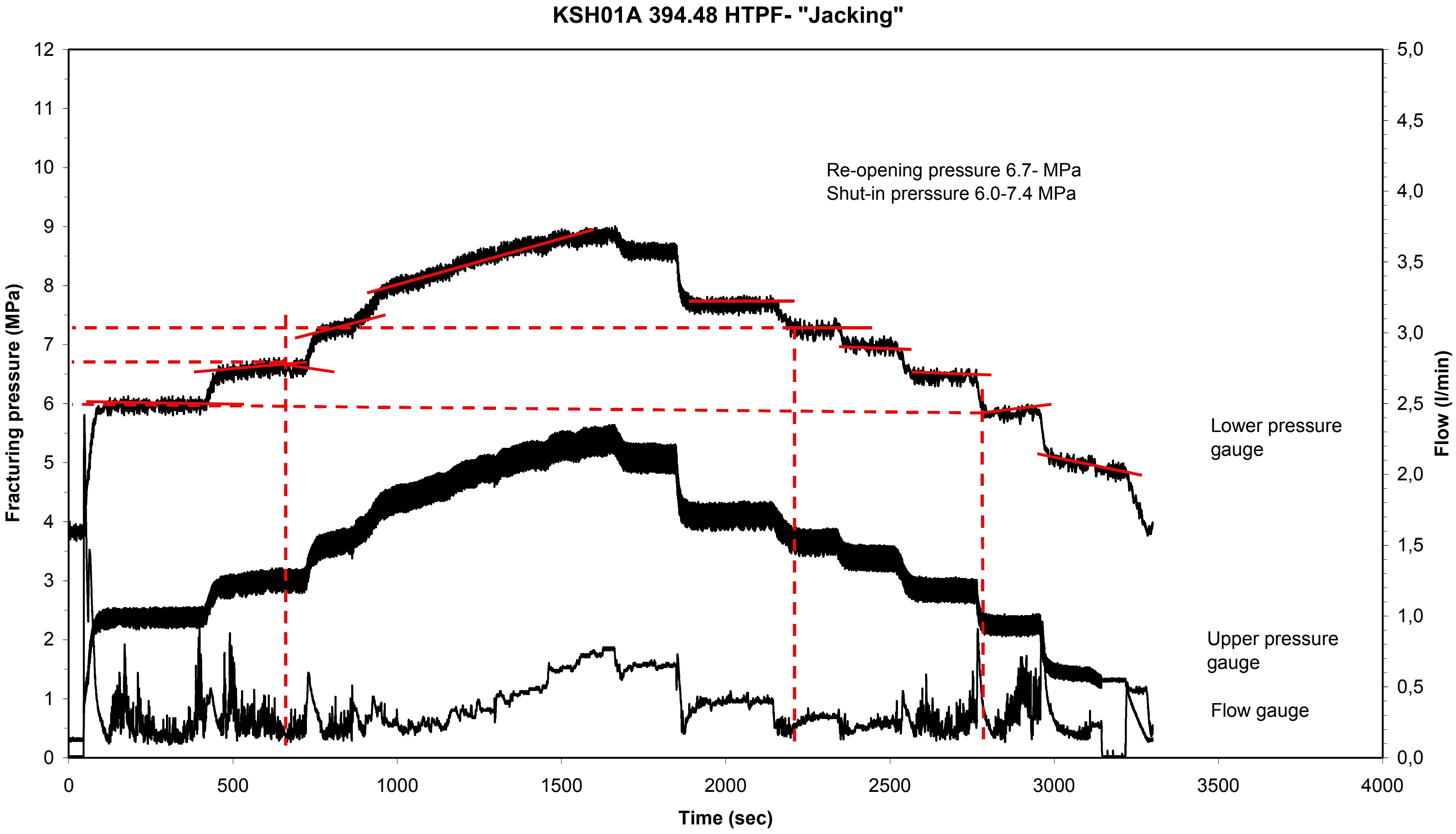


Figure B12. *Shut-in pressure determined from jacking test (HTPF) at 394.48 m borehole length.*

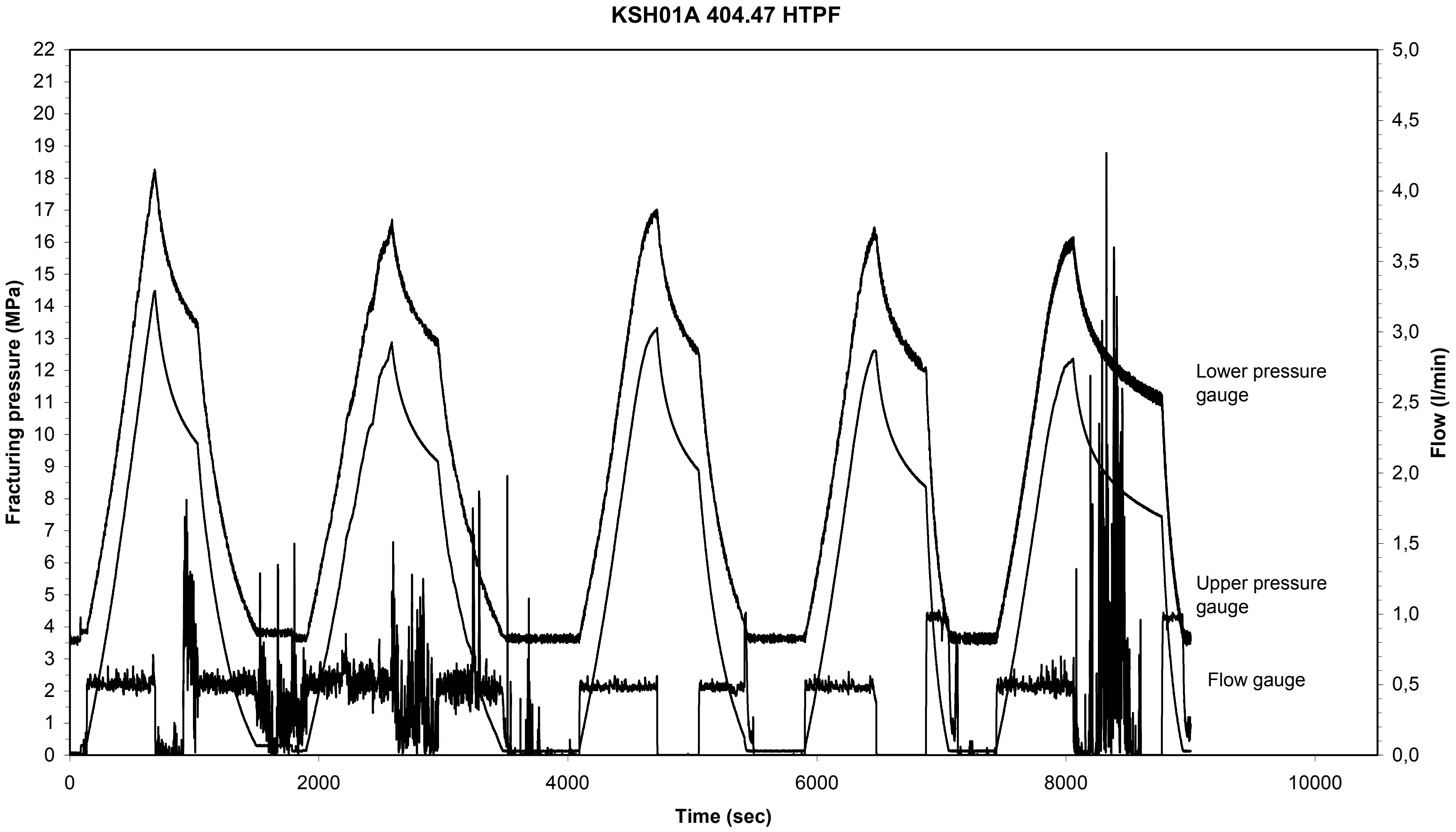


Figure B13. *Pressure and flow record during HTPF tests at 404.47 m borehole length.*

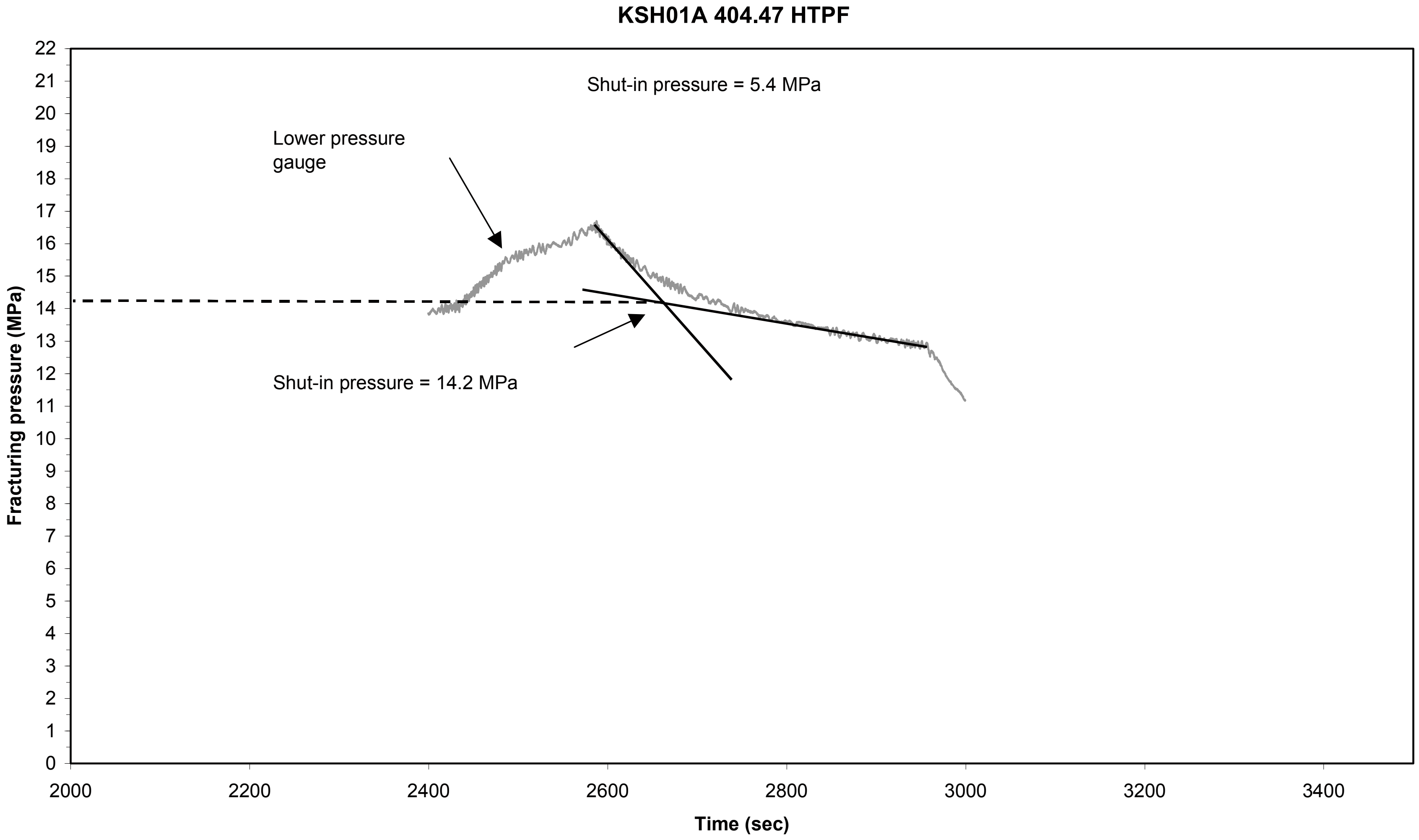


Figure B14. *Shut-in pressure determined with tangent intersection method from HTPF at 404.47 m borehole length.*

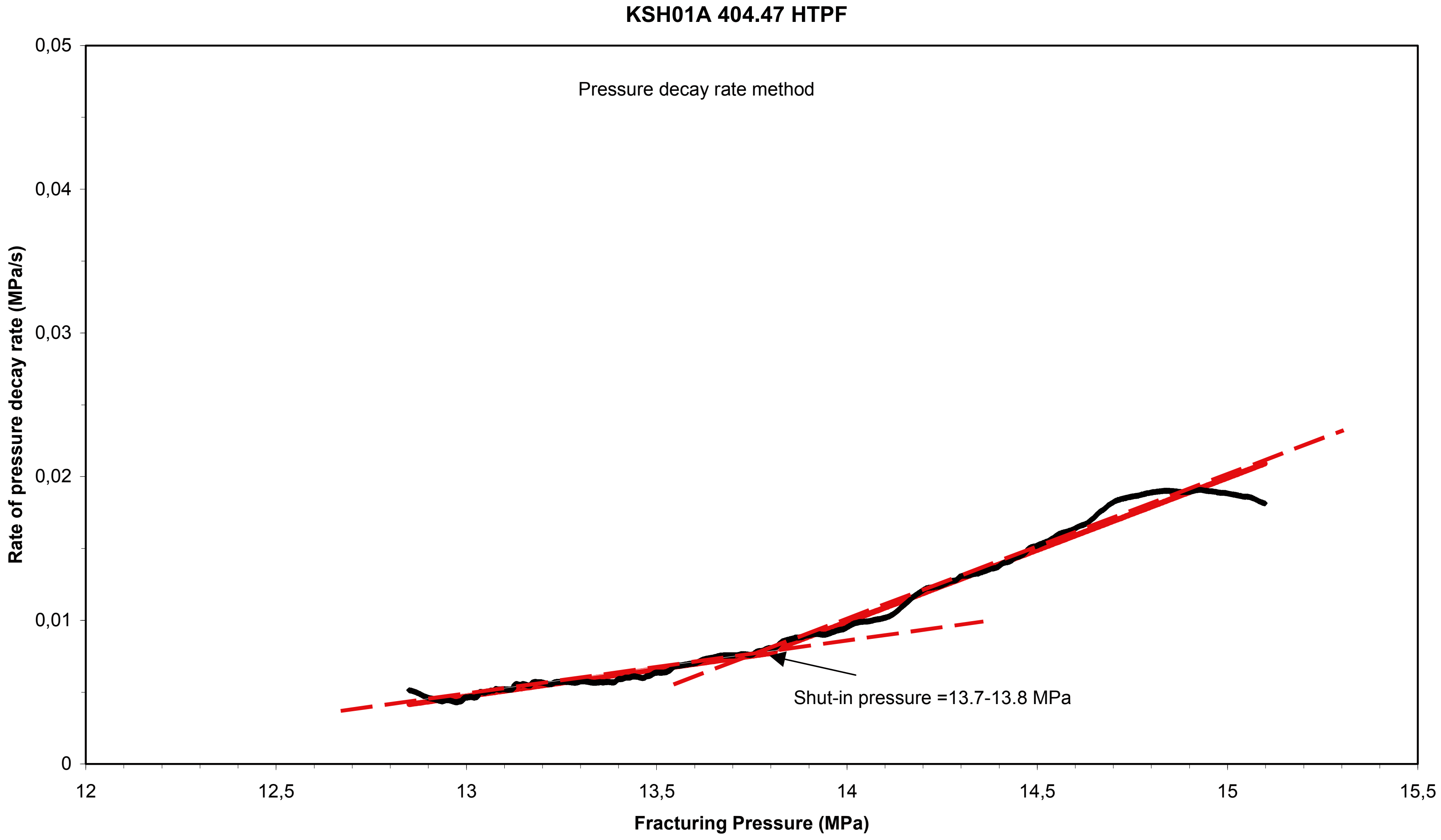


Figure B15. *Shut-in pressure determined by the decay rate method from HTPF at 404.47 m borehole length.*

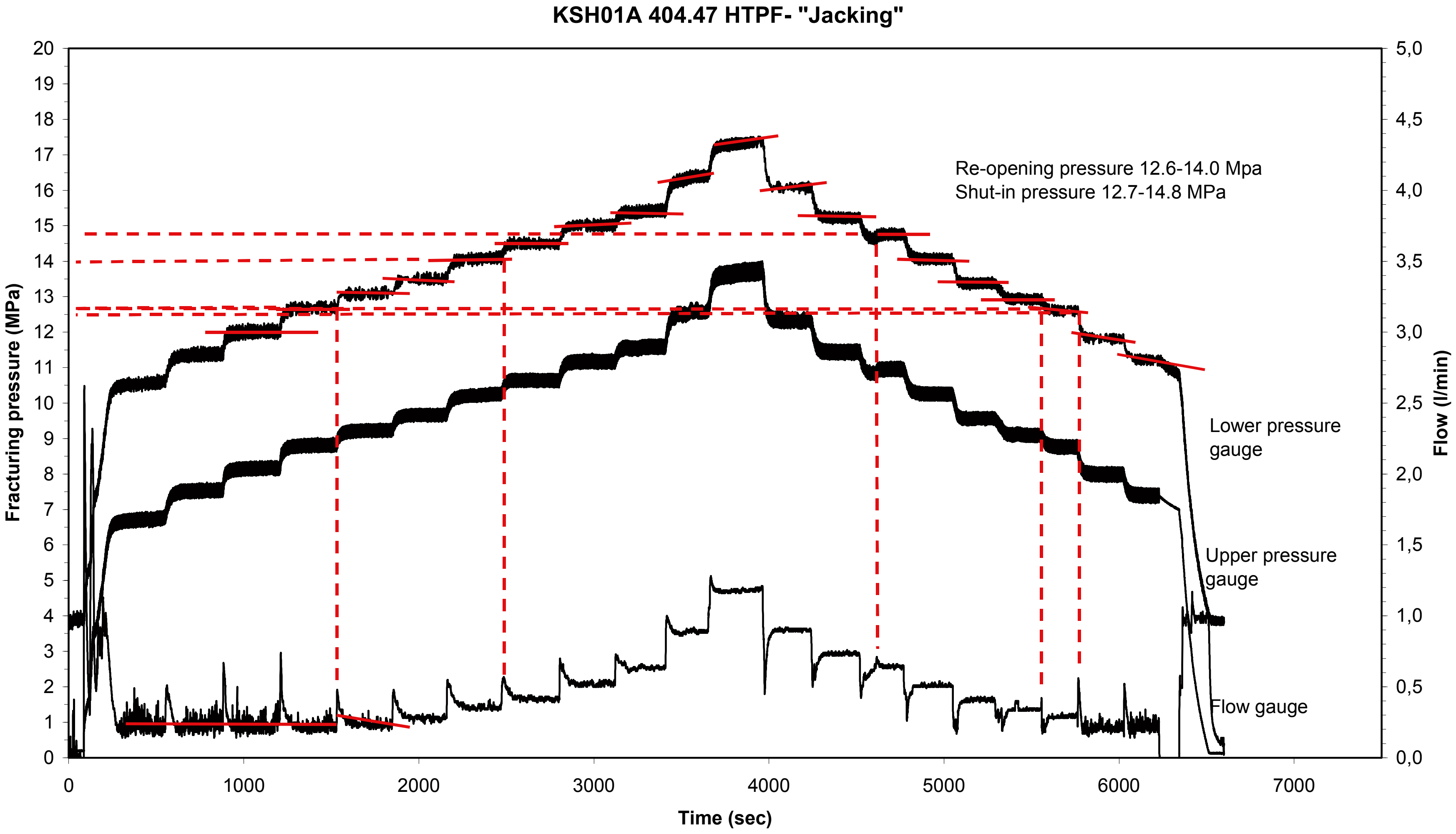


Figure B16. *Shut-in pressure determined from jacking test (HTPF) at 404.47 m borehole length.*

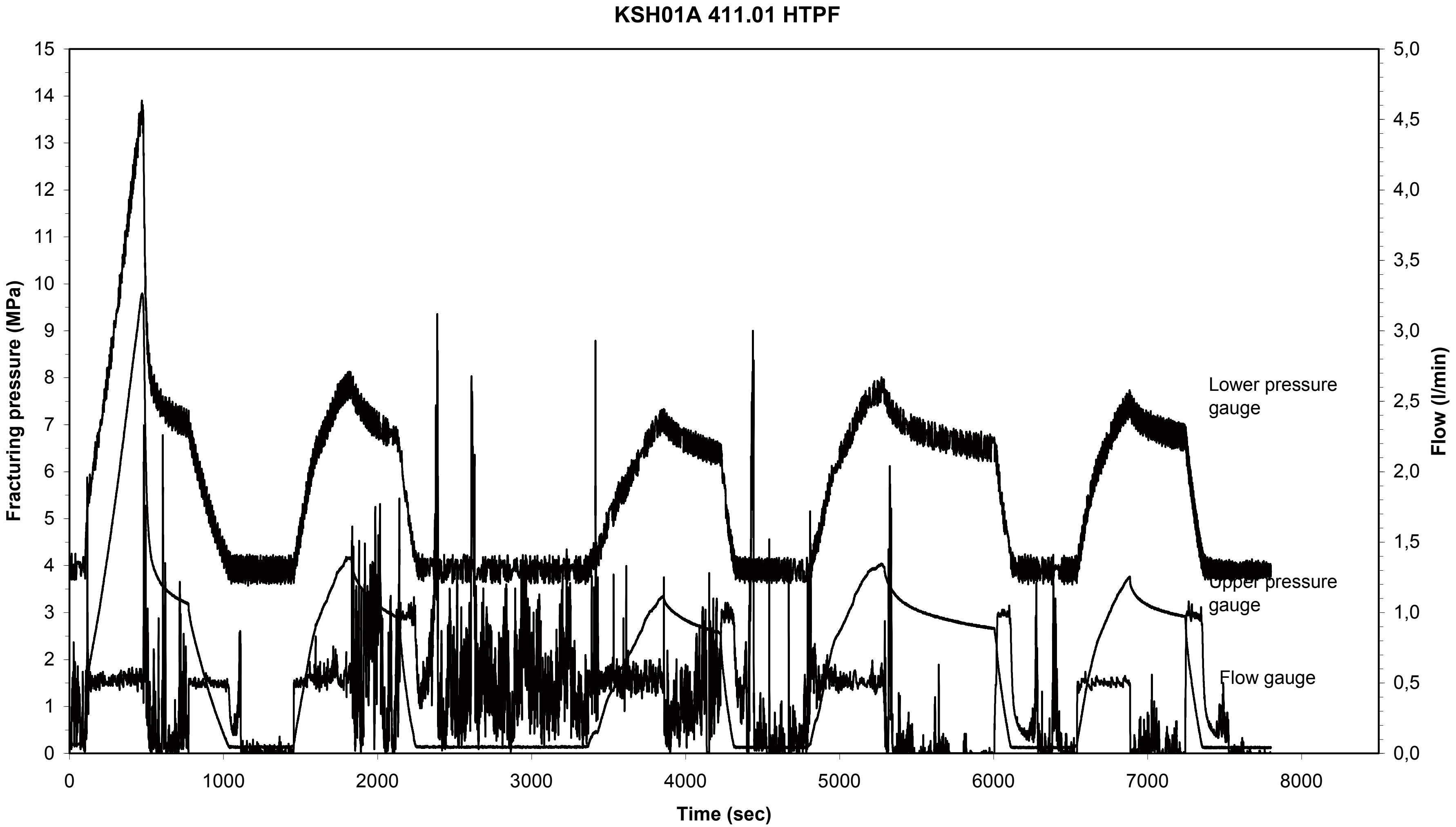


Figure B17. *Pressure and flow record during HTPF tests at 411.01 m borehole length.*

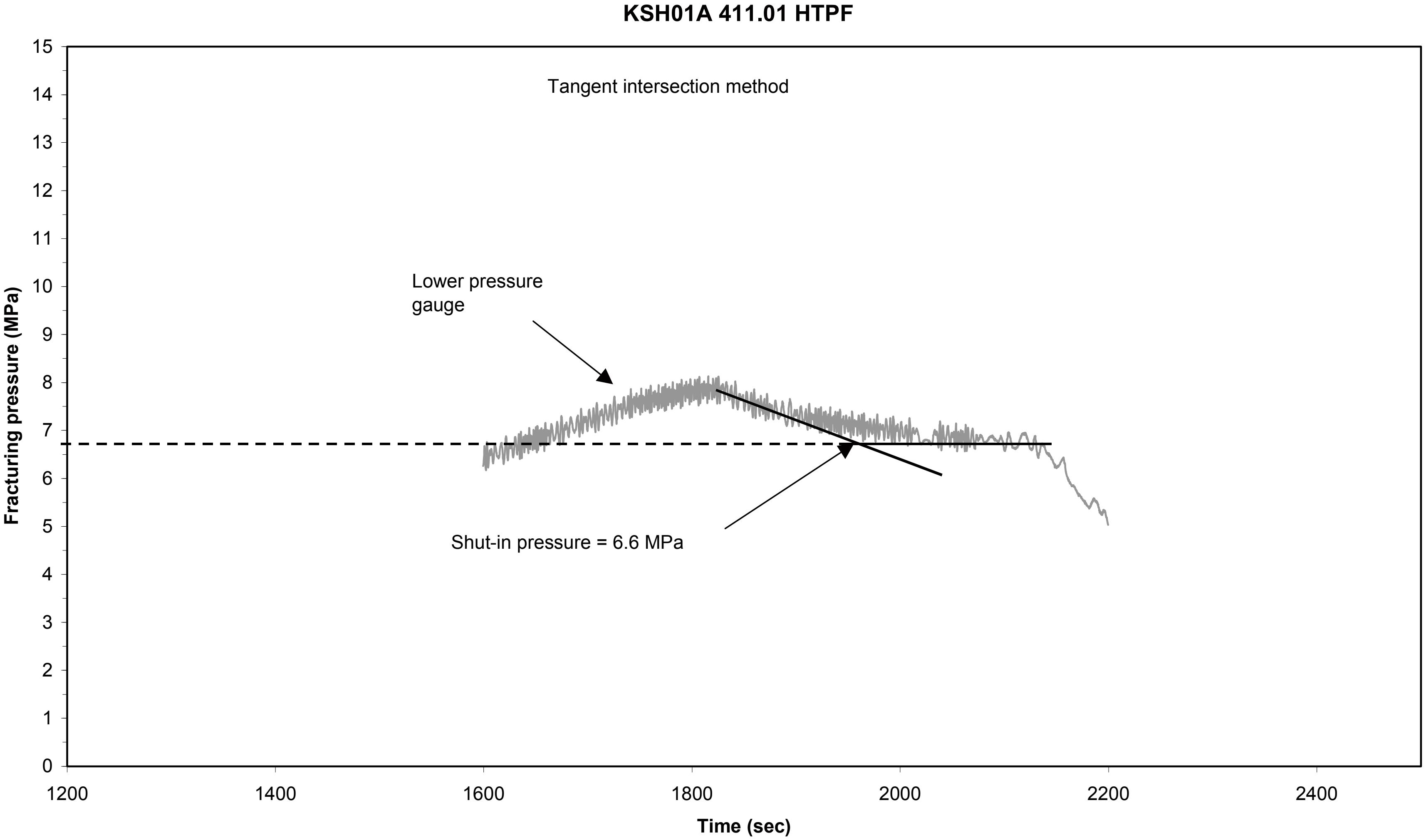


Figure B18. *Shut-in pressure determined with tangent intersection method from HTPF at 411.01 m borehole length.*

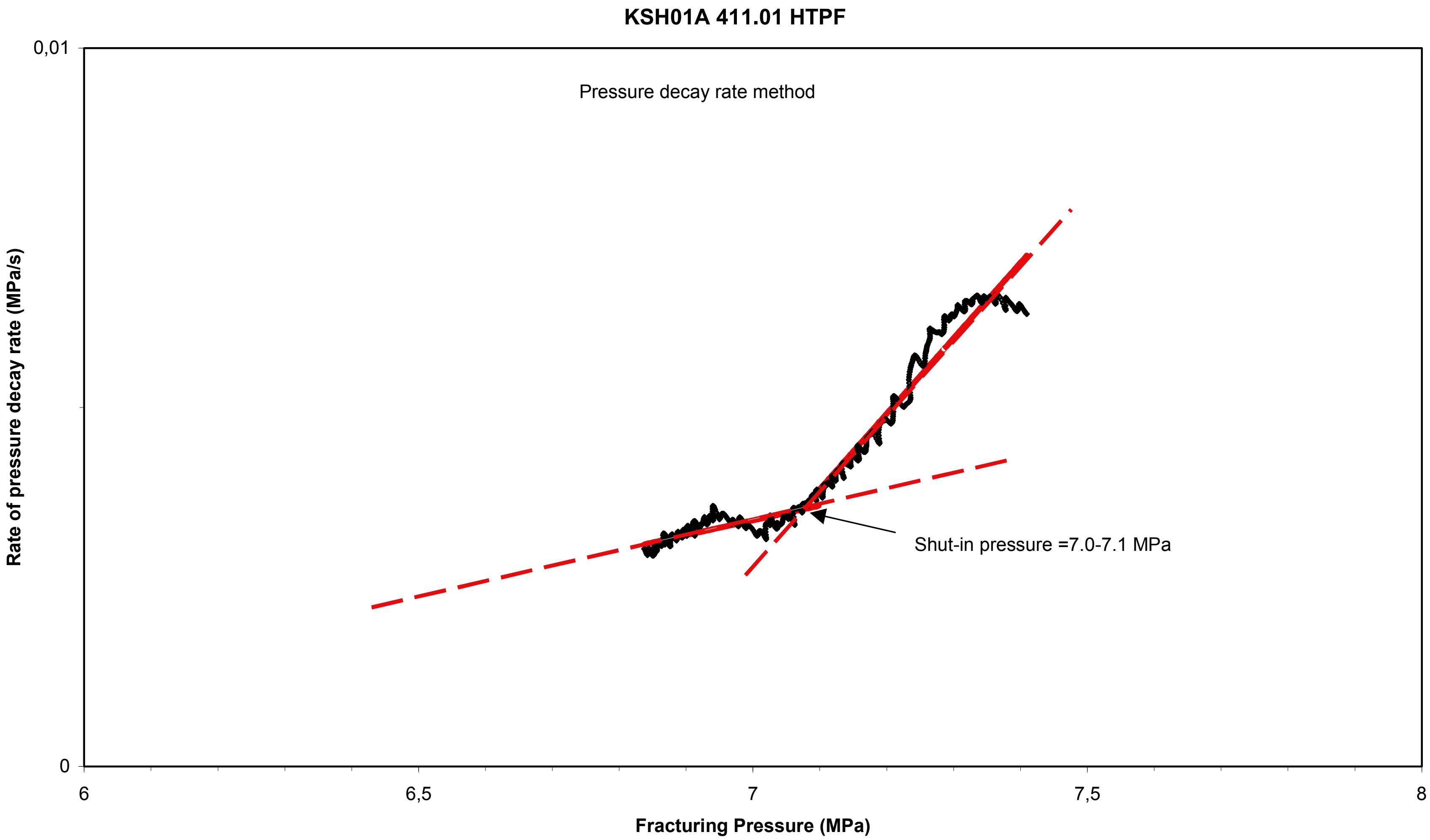


Figure B19. *Shut-in pressure determined by the decay rate method from HTPF at 411.01 m borehole length.*

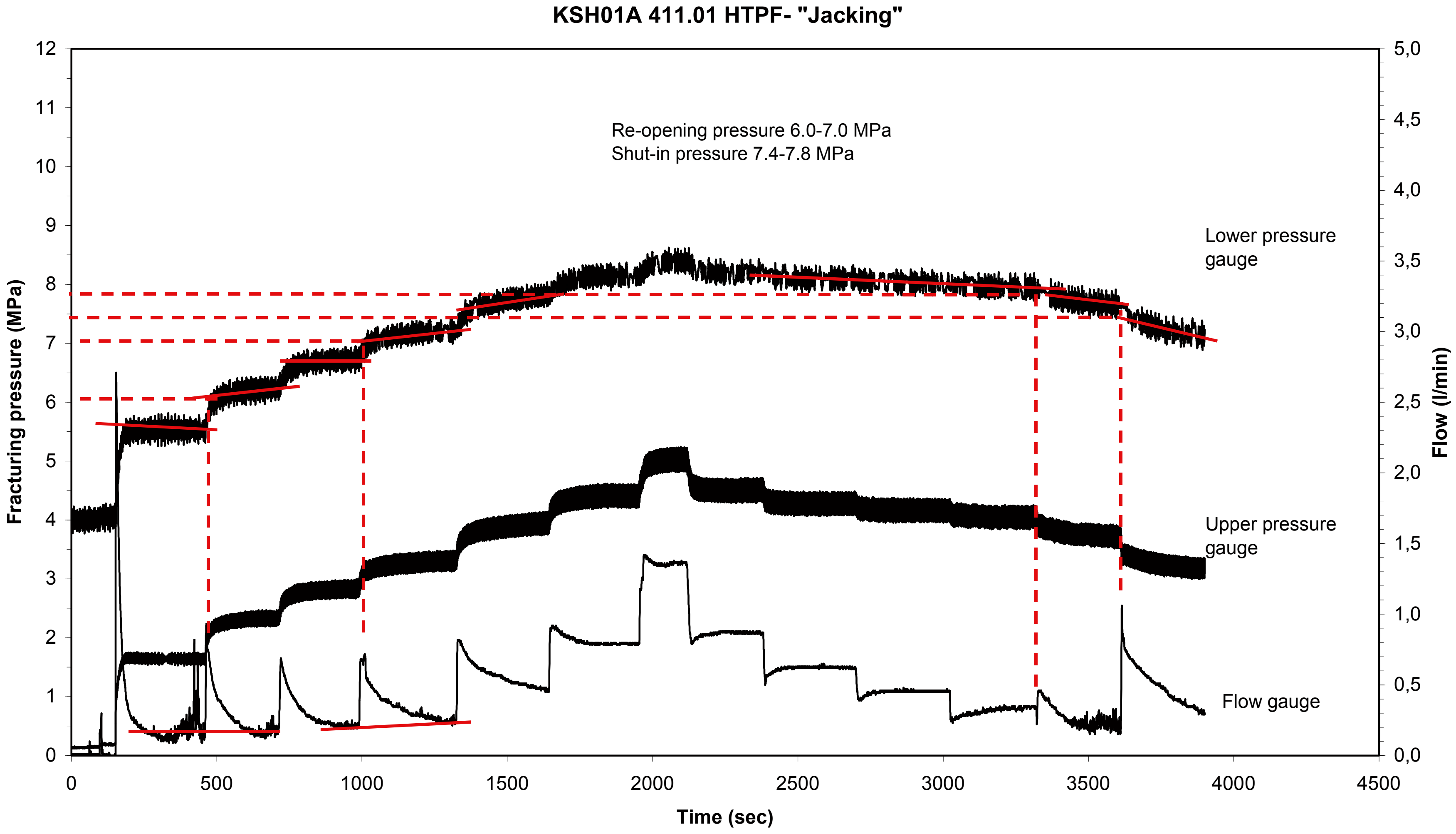


Figure B20. *Shut-in pressure determined from jacking test (HTPF) at 411.01 m borehole length.*

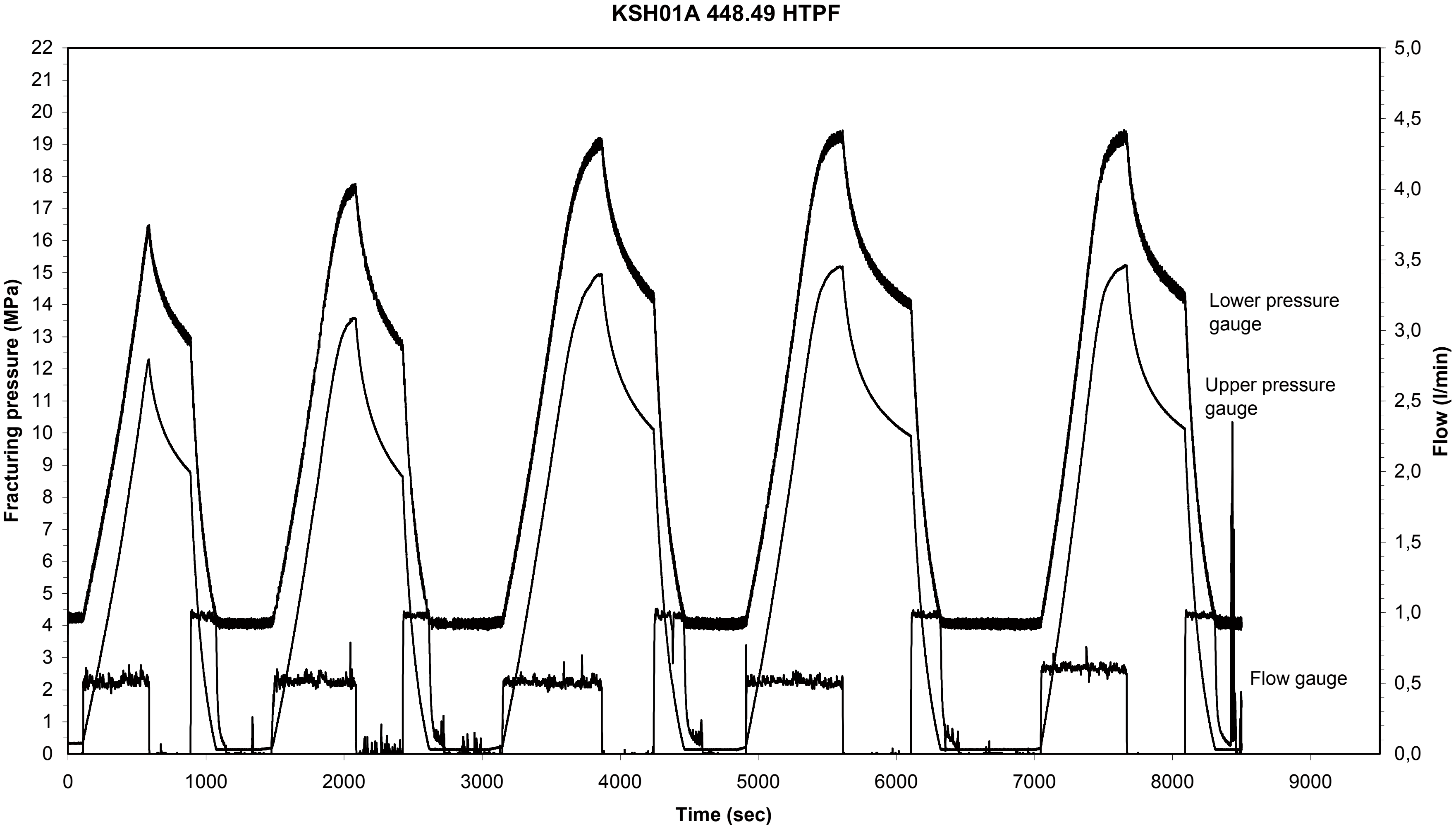


Figure B21. *Pressure and flow record during HTPF tests at 448.49 m borehole length.*

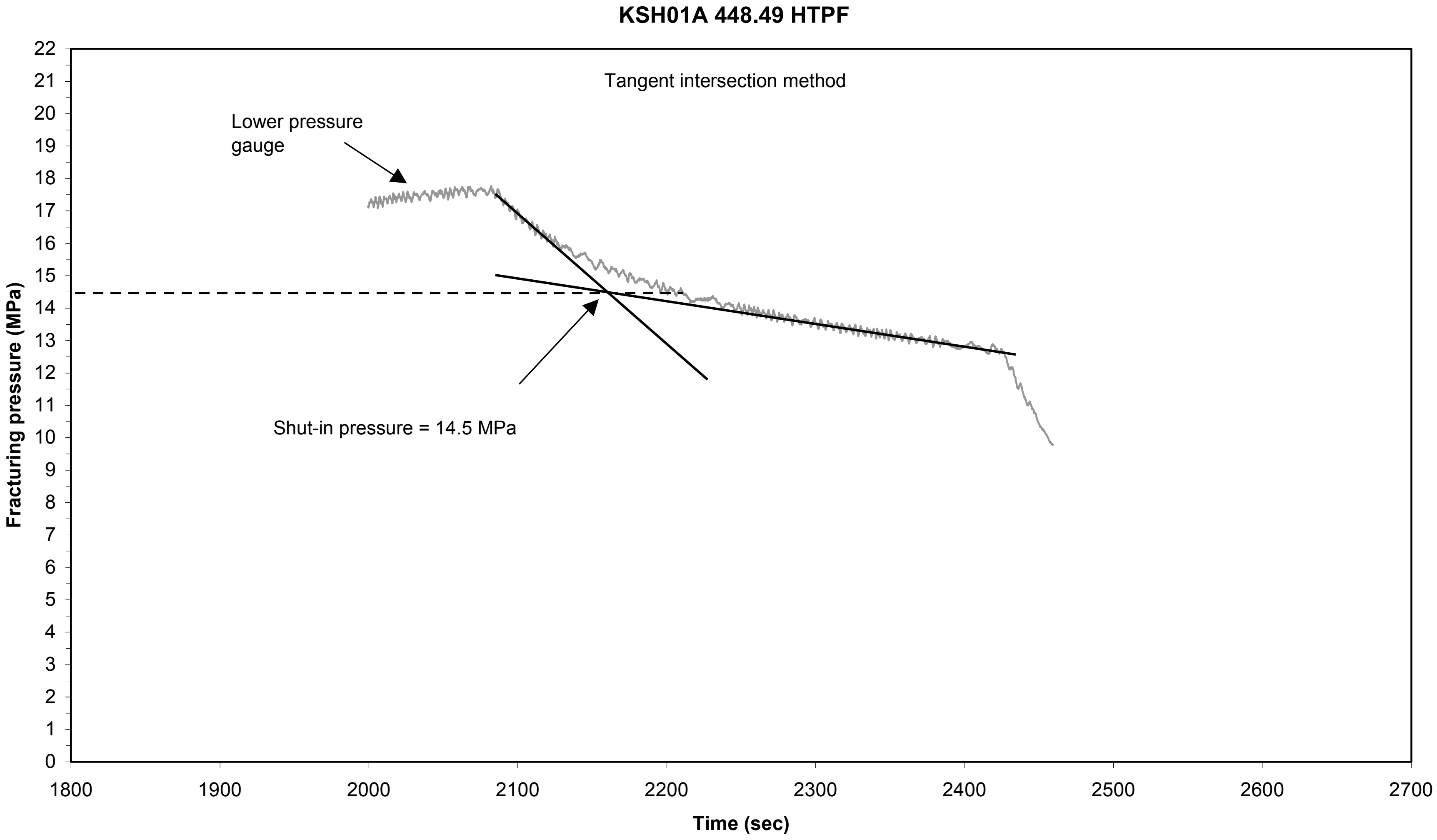


Figure B22. *Shut-in pressure determined with tangent intersection method from HTPF at 448.49 m borehole length.*

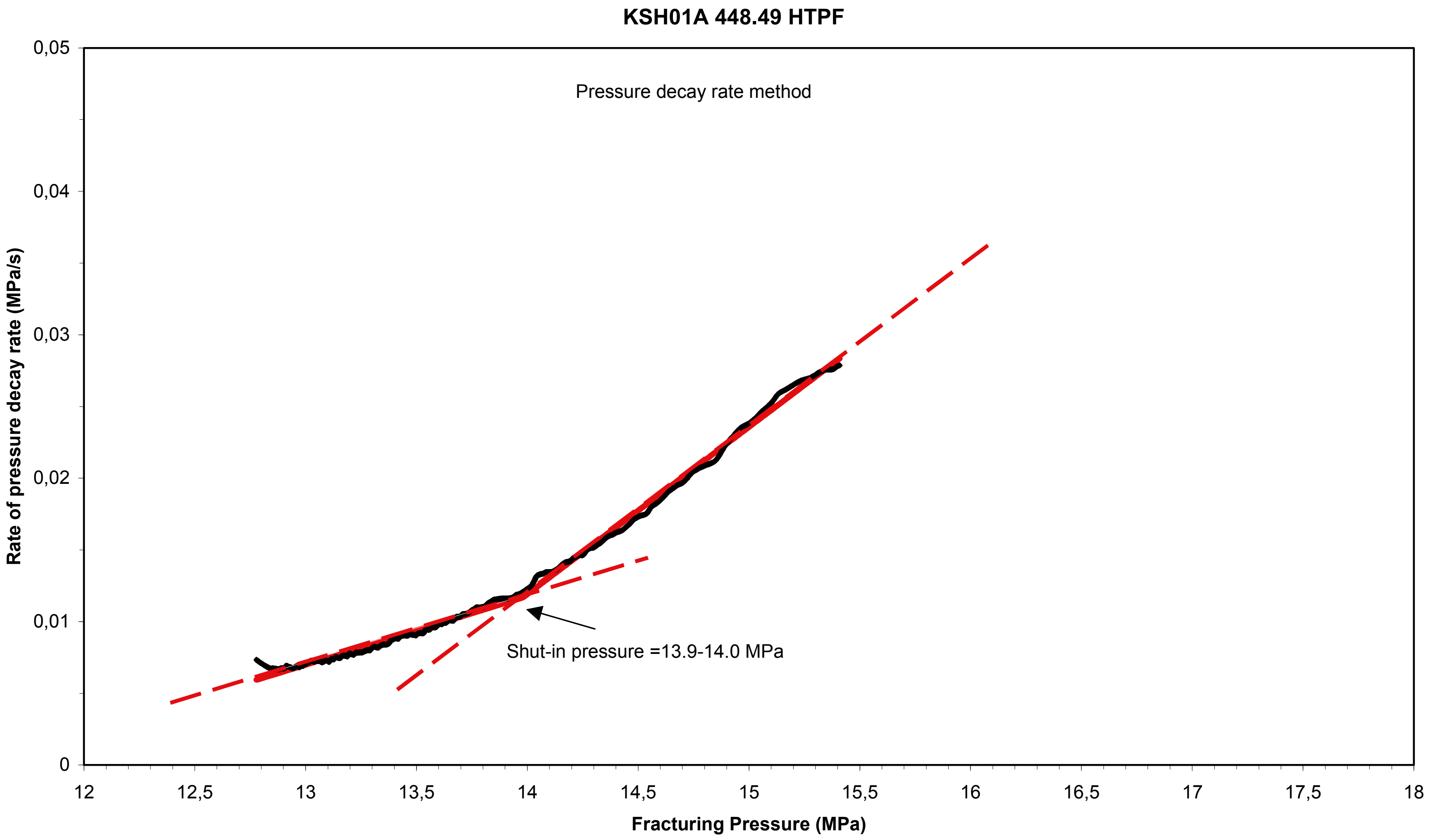


Figure B23. *Shut-in pressure determined by the decay rate method from HTPF at 448.49 m borehole length.*

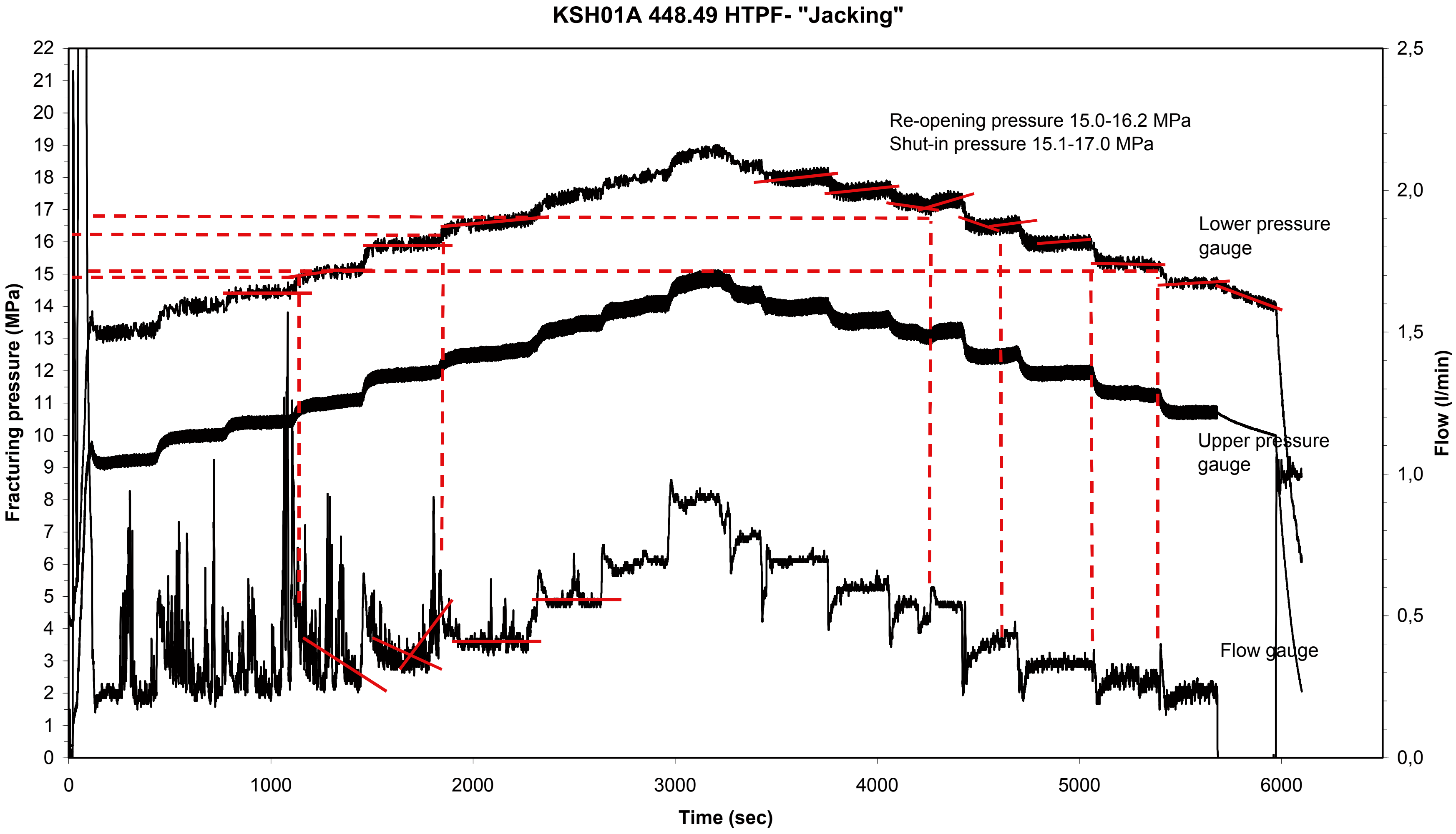


Figure B24. *Shut-in pressure determined from jacking test (HTPF) at 448.49 m borehole length.*

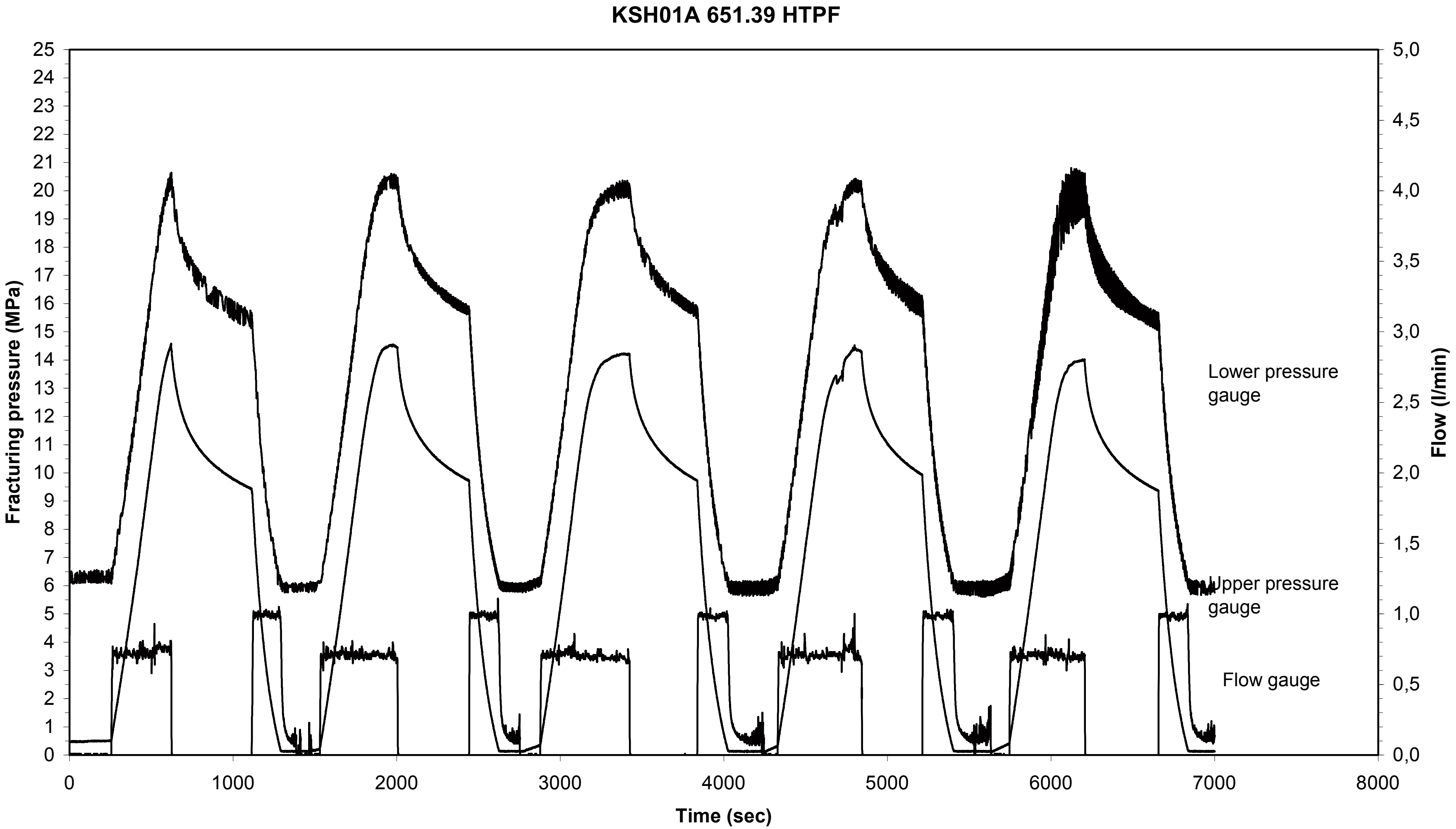


Figure B25. *Pressure and flow record during HTPF tests at 651.39 m borehole length.*

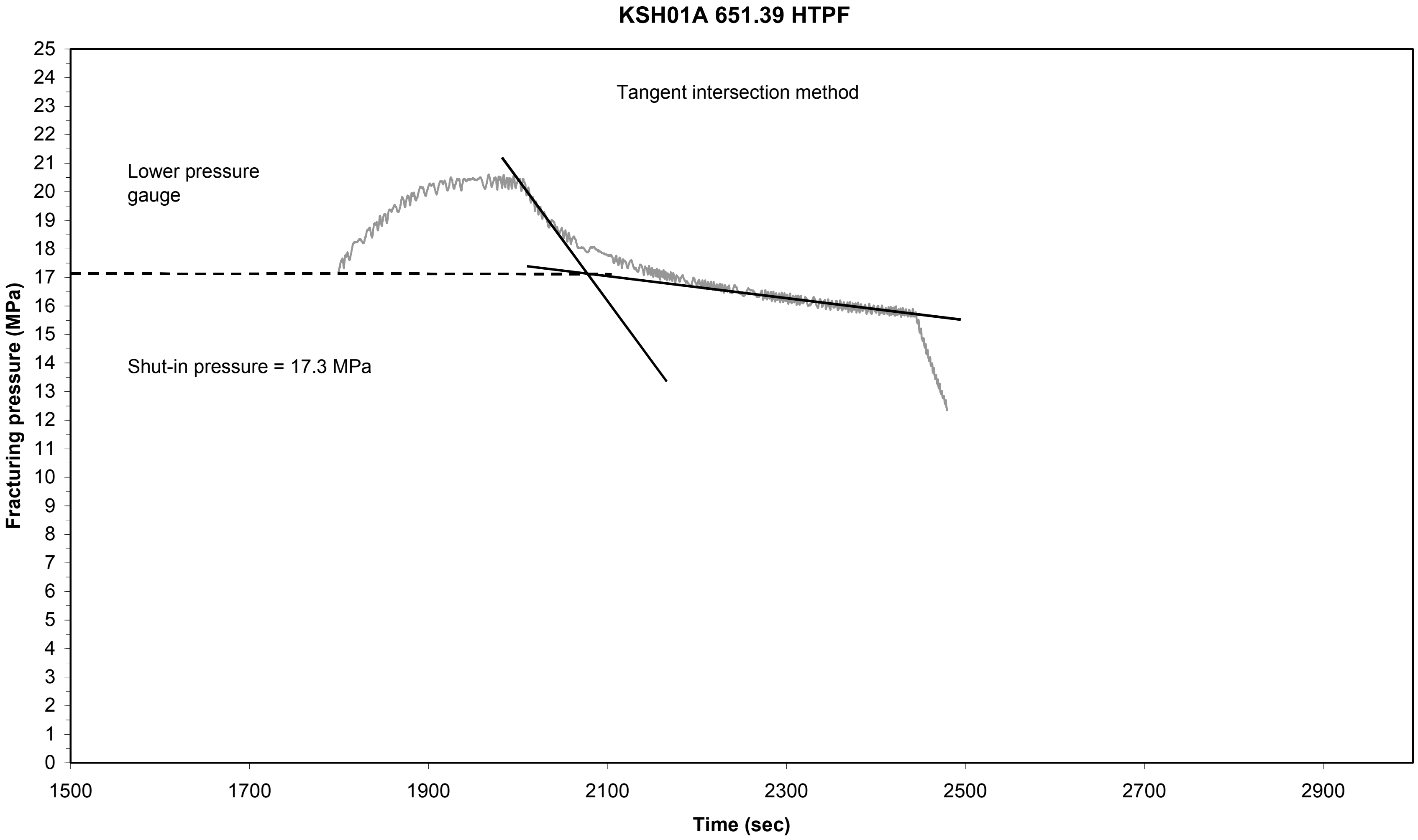


Figure B26. *Shut-in pressure determined with tangent intersection method from HTPF at 651.39 m borehole length.*

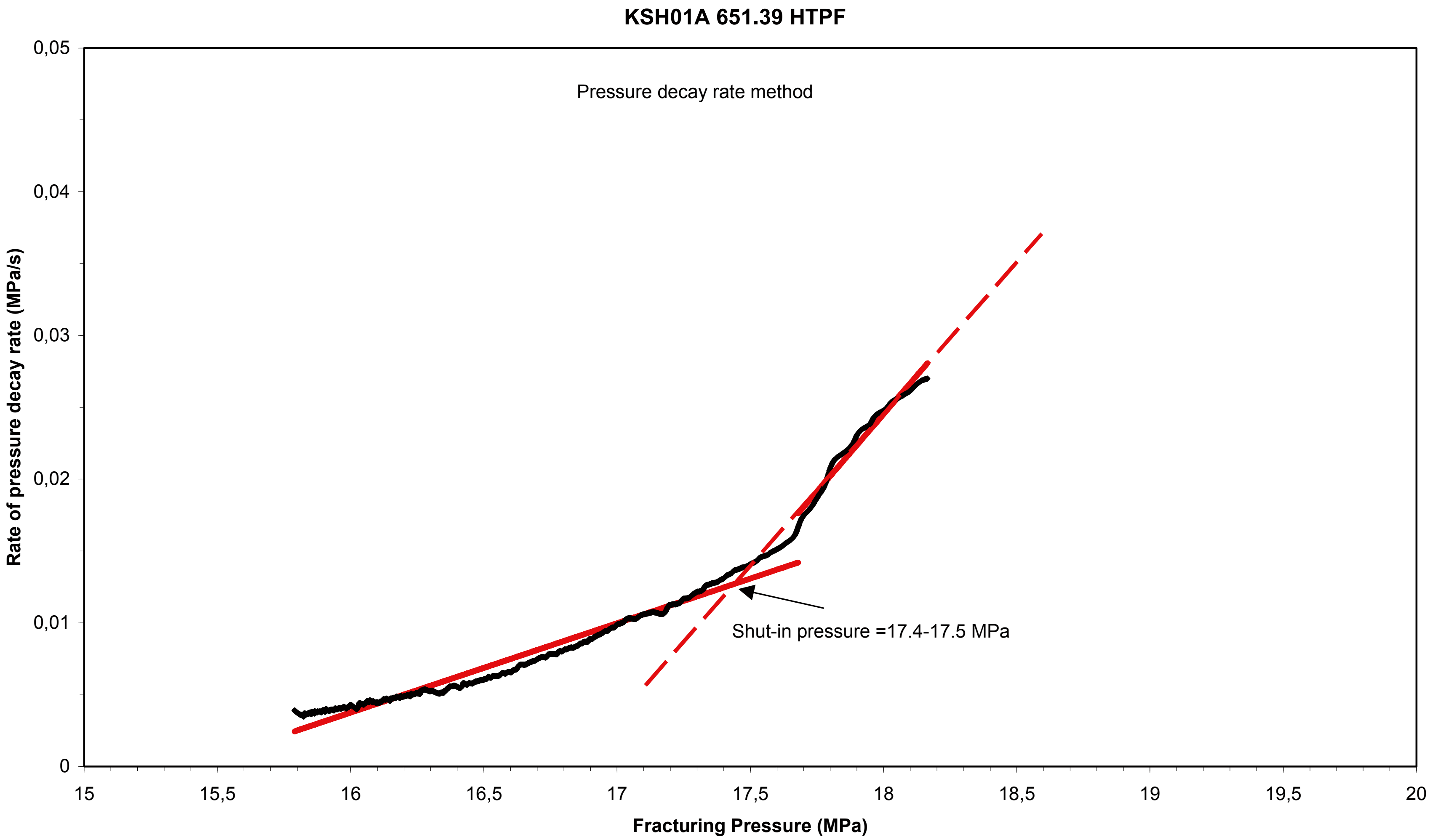


Figure B27. *Shut-in pressure determined by the decay rate method from HTPF at 651.39 m borehole length.*

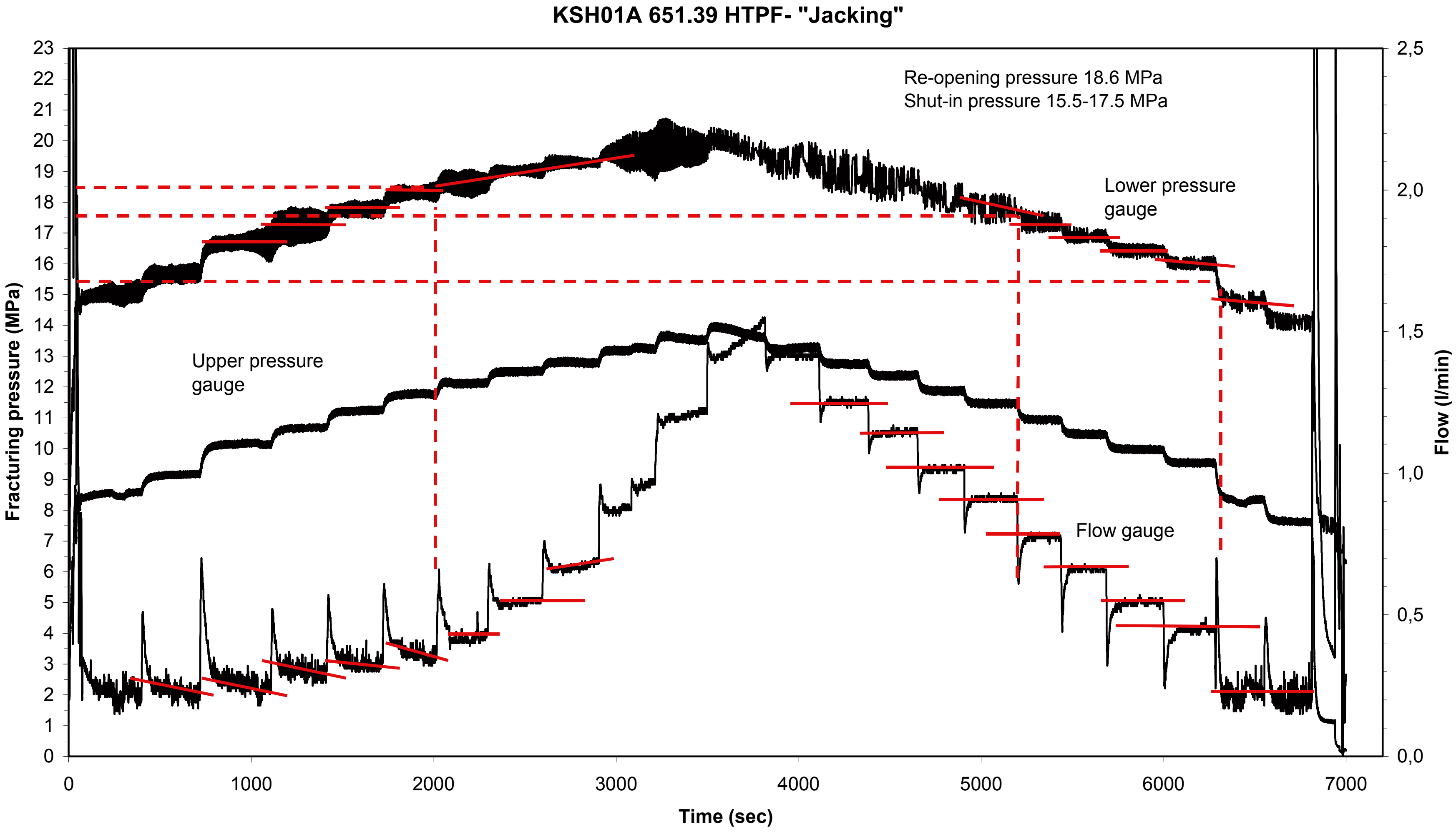


Figure B28. *Shut-in pressure determined from jacking test (HTPF) at 651.39 m borehole length.*

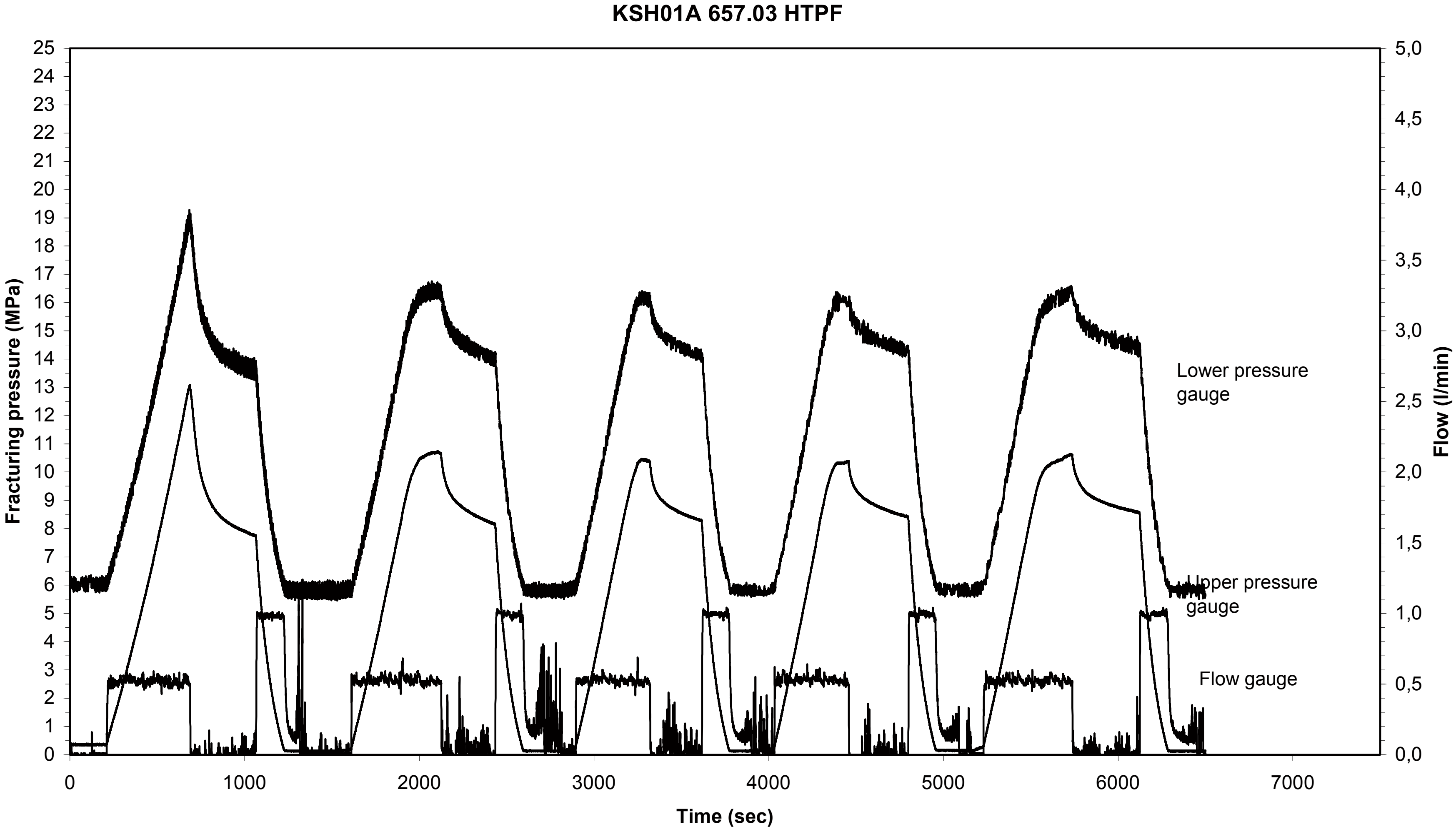


Figure B29. *Pressure and flow record during HTPF tests at 657.03 m borehole length.*

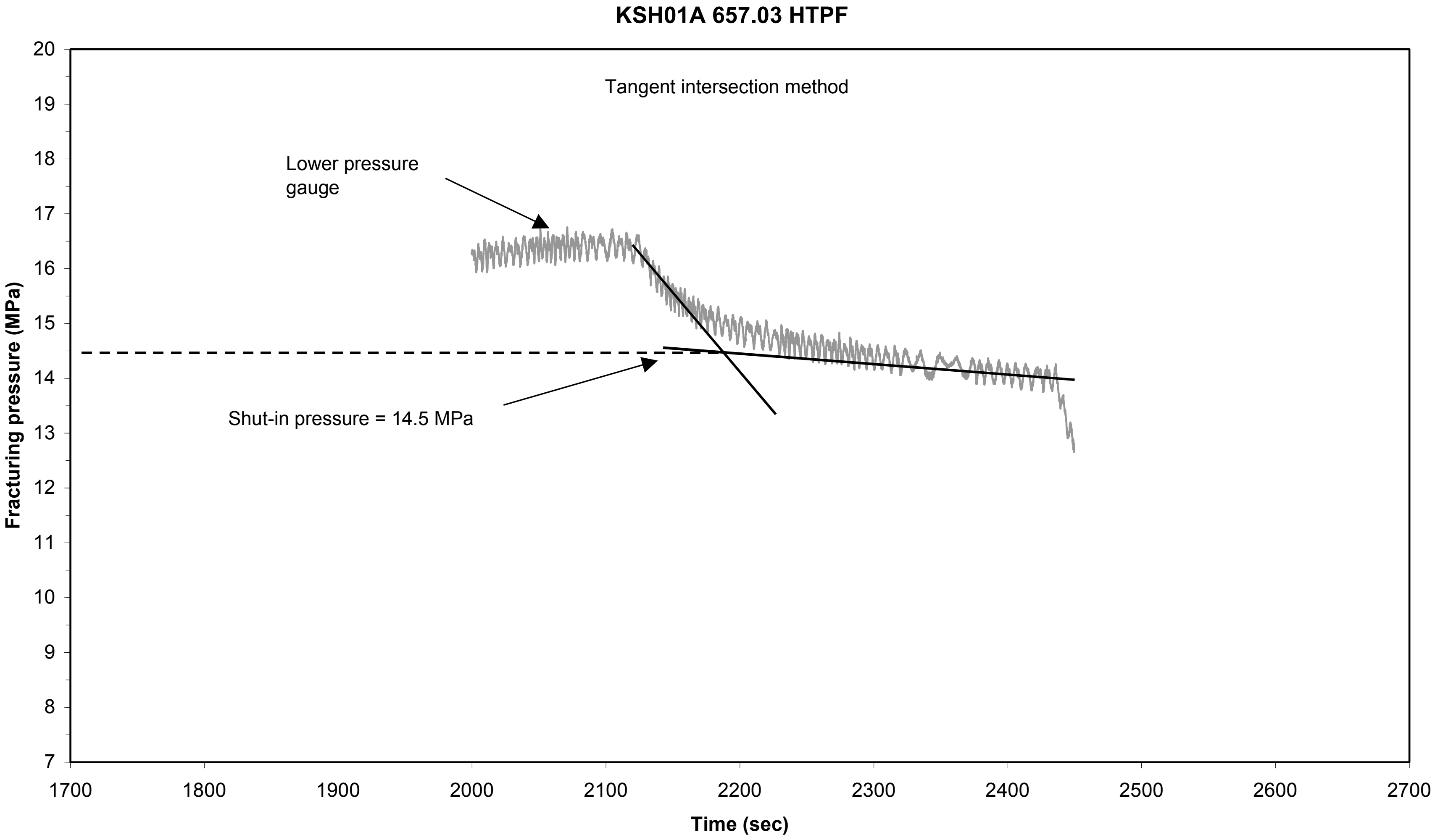


Figure B30. *Shut-in pressure determined with tangent intersection method from HTPF at 657.03 m borehole length.*

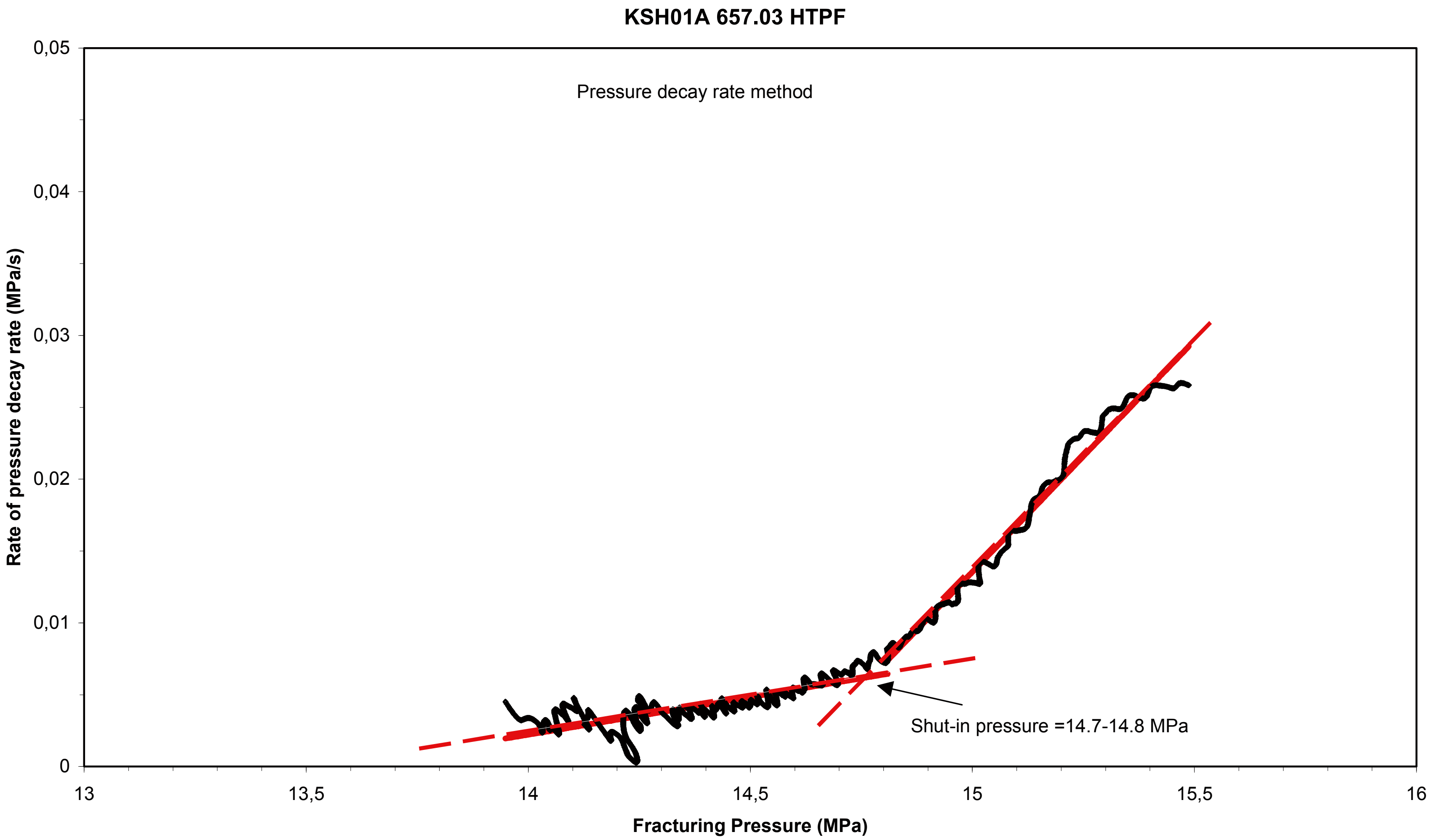


Figure B31. *Shut-in pressure determined by the decay rate method from HTPF at 657.03 m borehole length.*

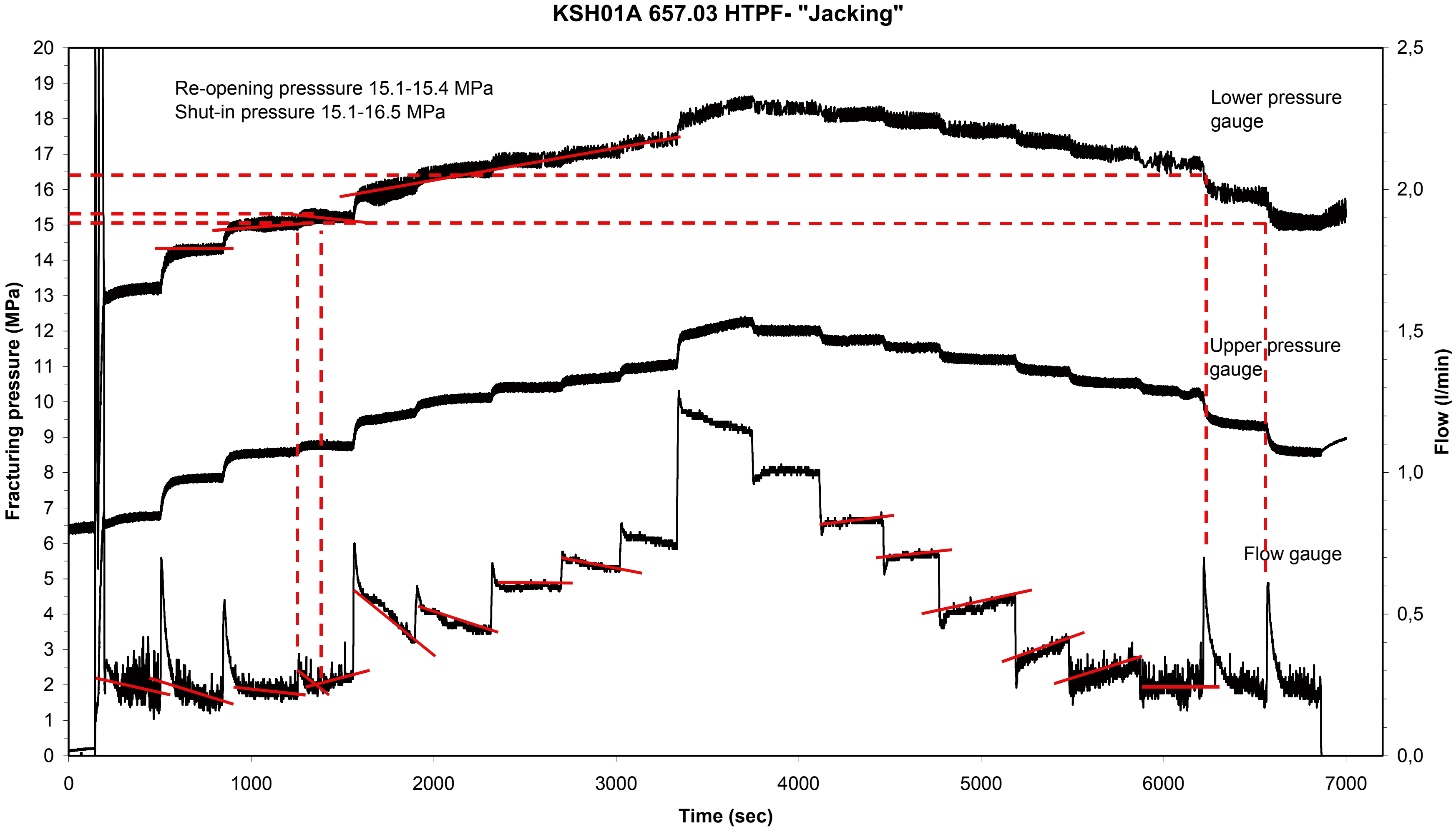


Figure B32. *Shut-in pressure determined from jacking test (HTPF) at 657.03 m borehole length.*

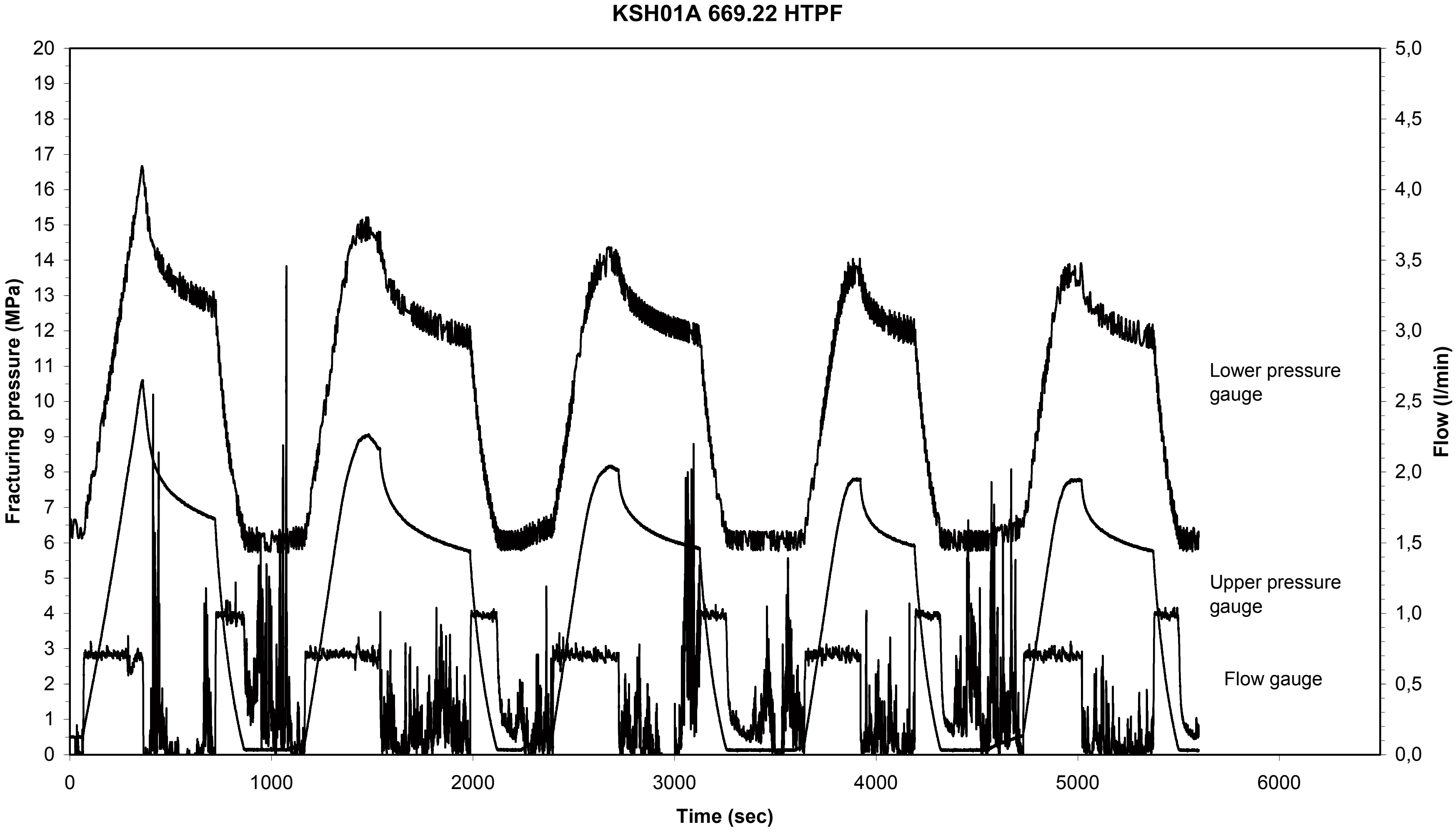


Figure B33. *Pressure and flow record during HTPF tests at 669.22 m borehole length.*

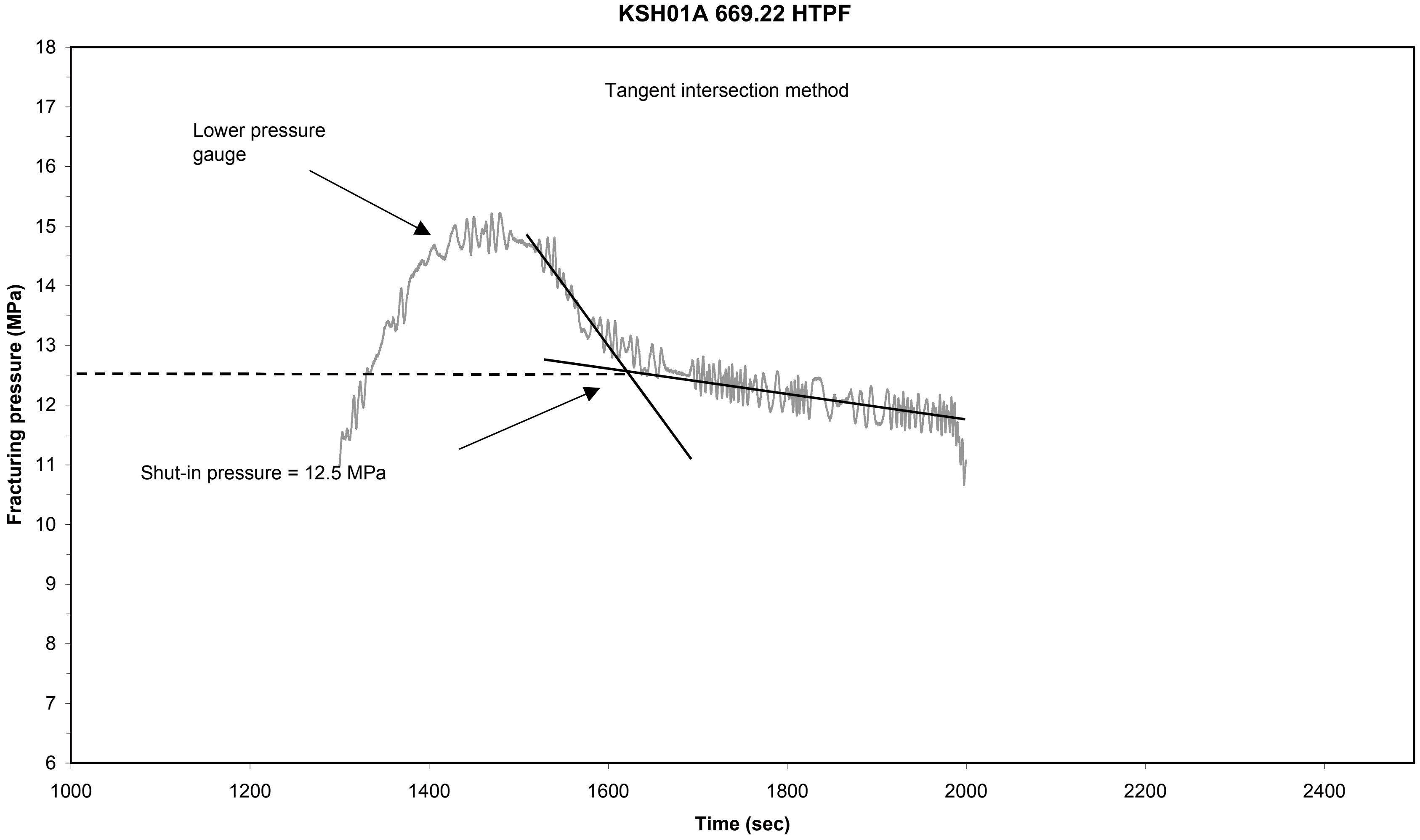


Figure B34. *Shut-in pressure determined with tangent intersection method from HTPF at 669.22 m borehole length.*

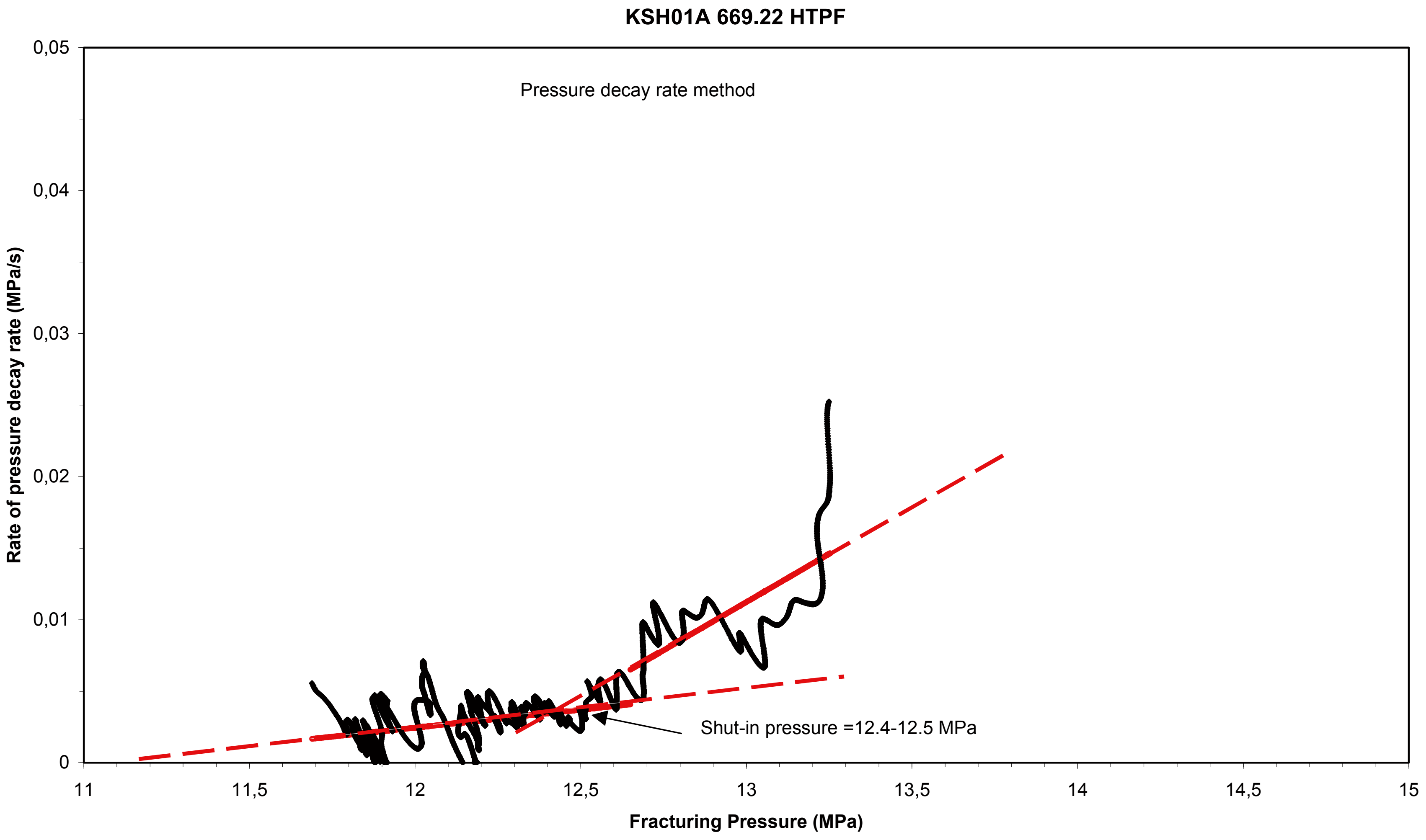


Figure B35. *Shut-in pressure determined by the decay rate method from HTPF at 669.22 m borehole length.*

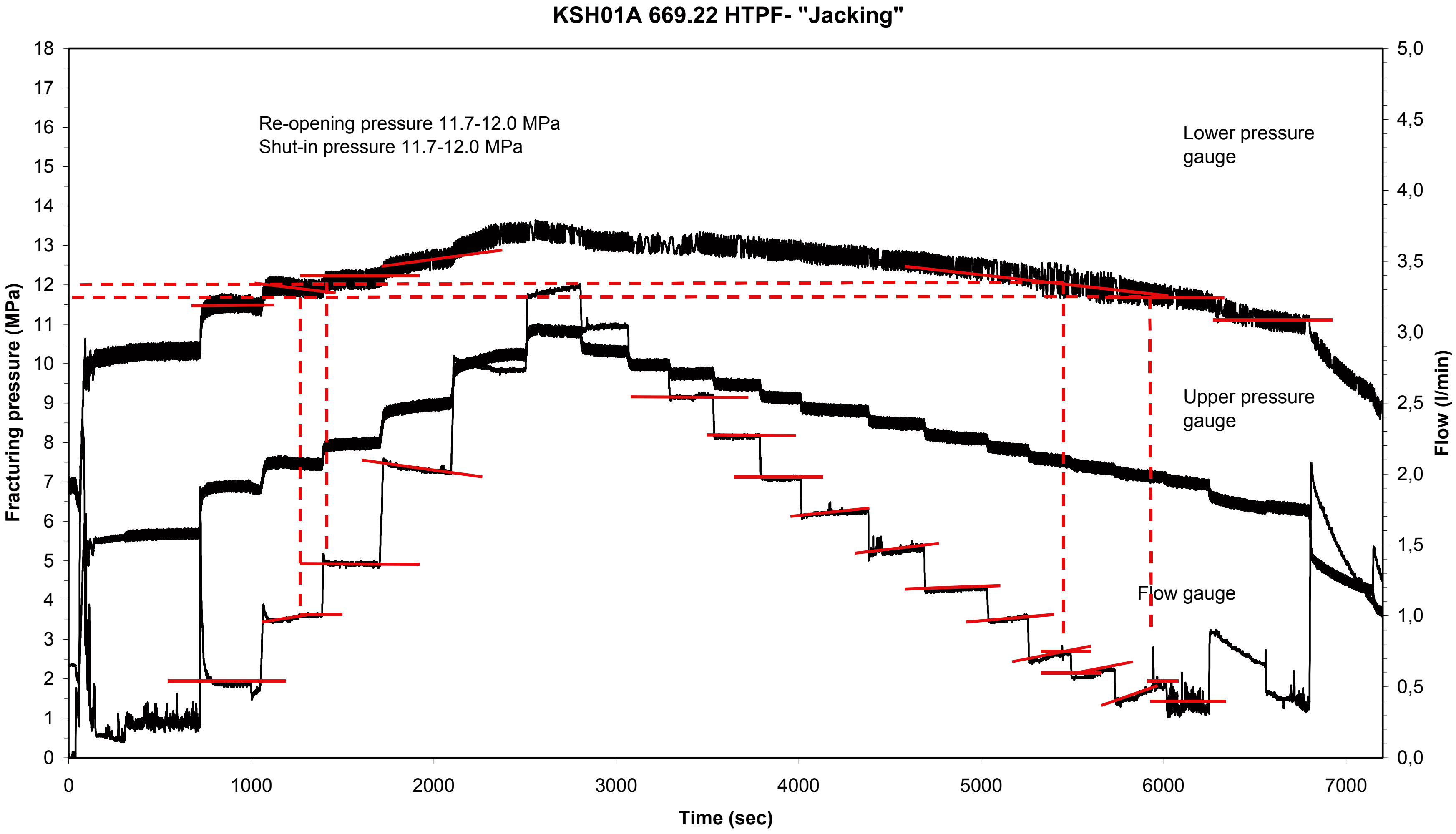


Figure B36. *Shut-in pressure determined from jacking test (HTPF) at 669.22 m borehole length.*

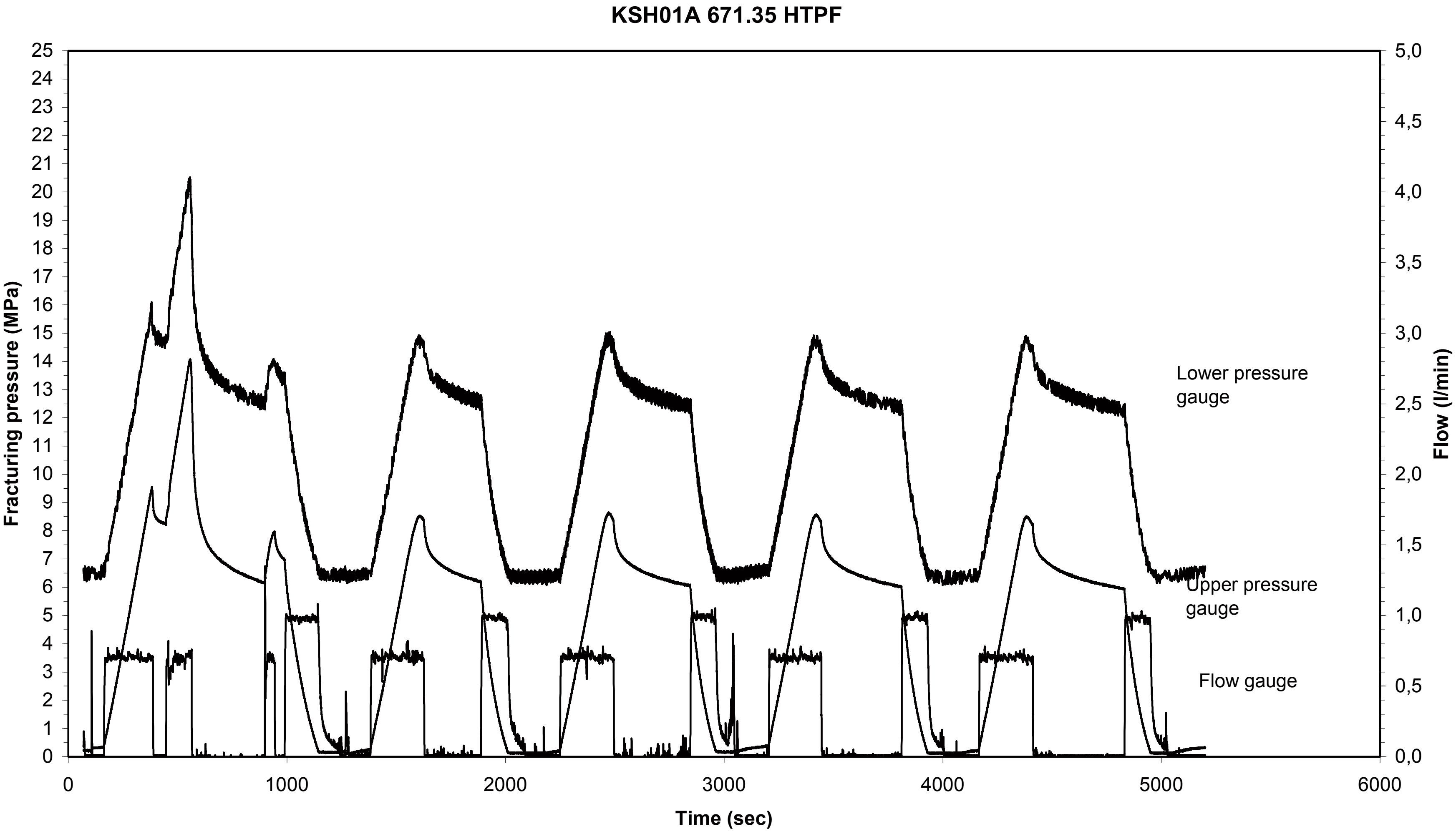


Figure B37. *Pressure and flow record during HTPF tests at 671.35 m borehole length.*

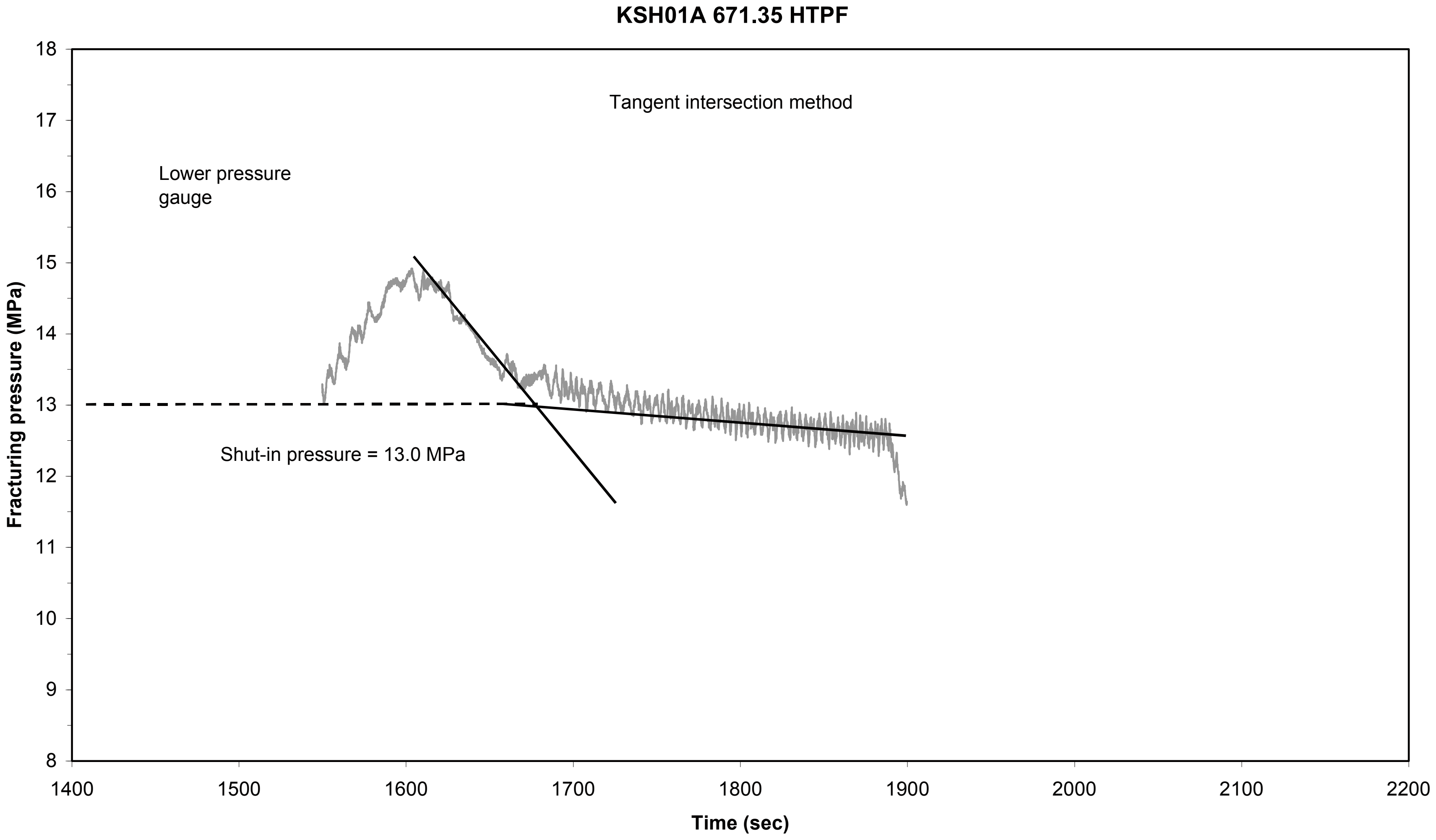


Figure B38. *Shut-in pressure determined with tangent intersection method from HTPF at 671.35 m borehole length.*

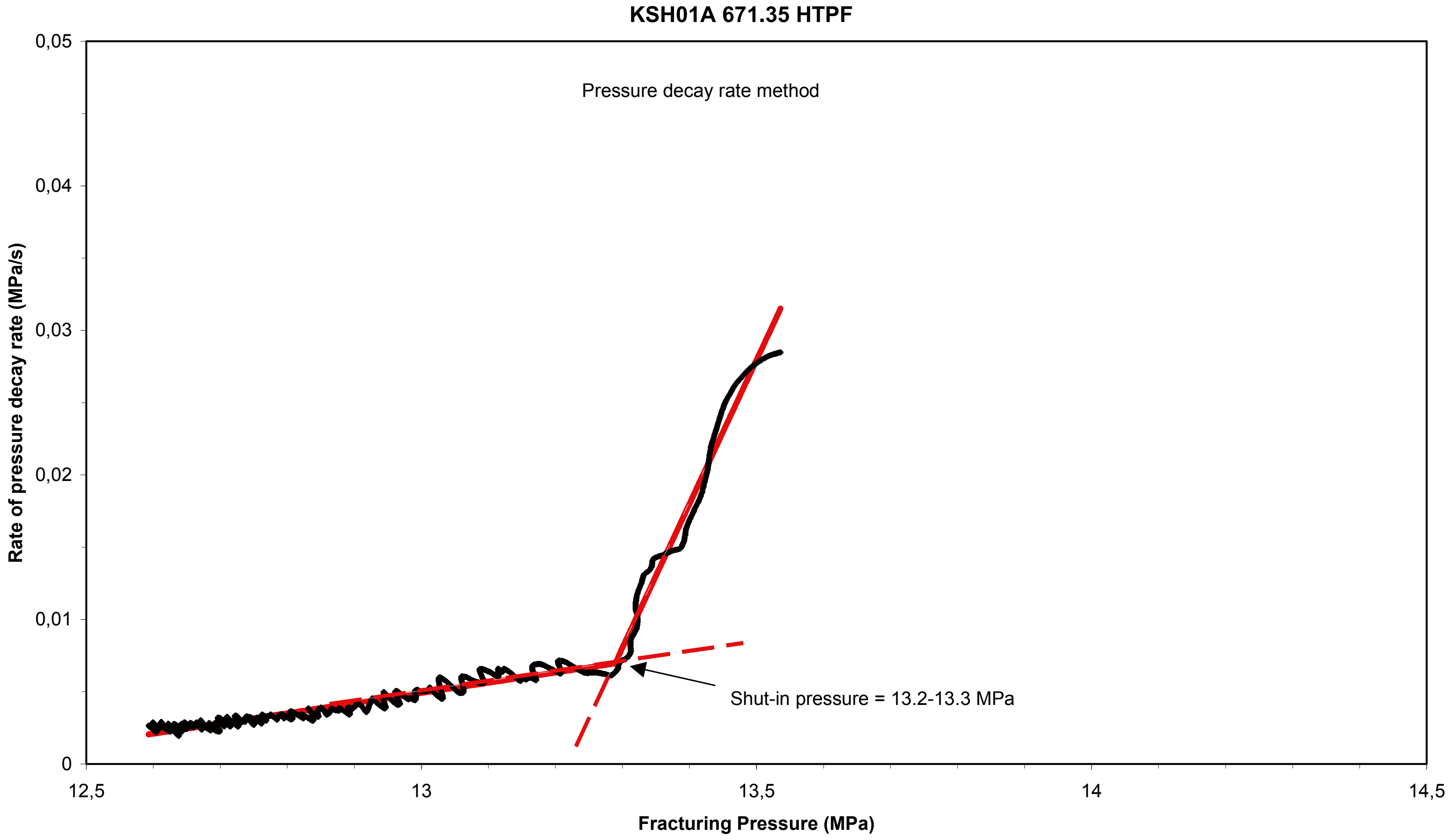


Figure B39. *Shut-in pressure determined by the decay rate method from HTPF at 671.35 m borehole length.*

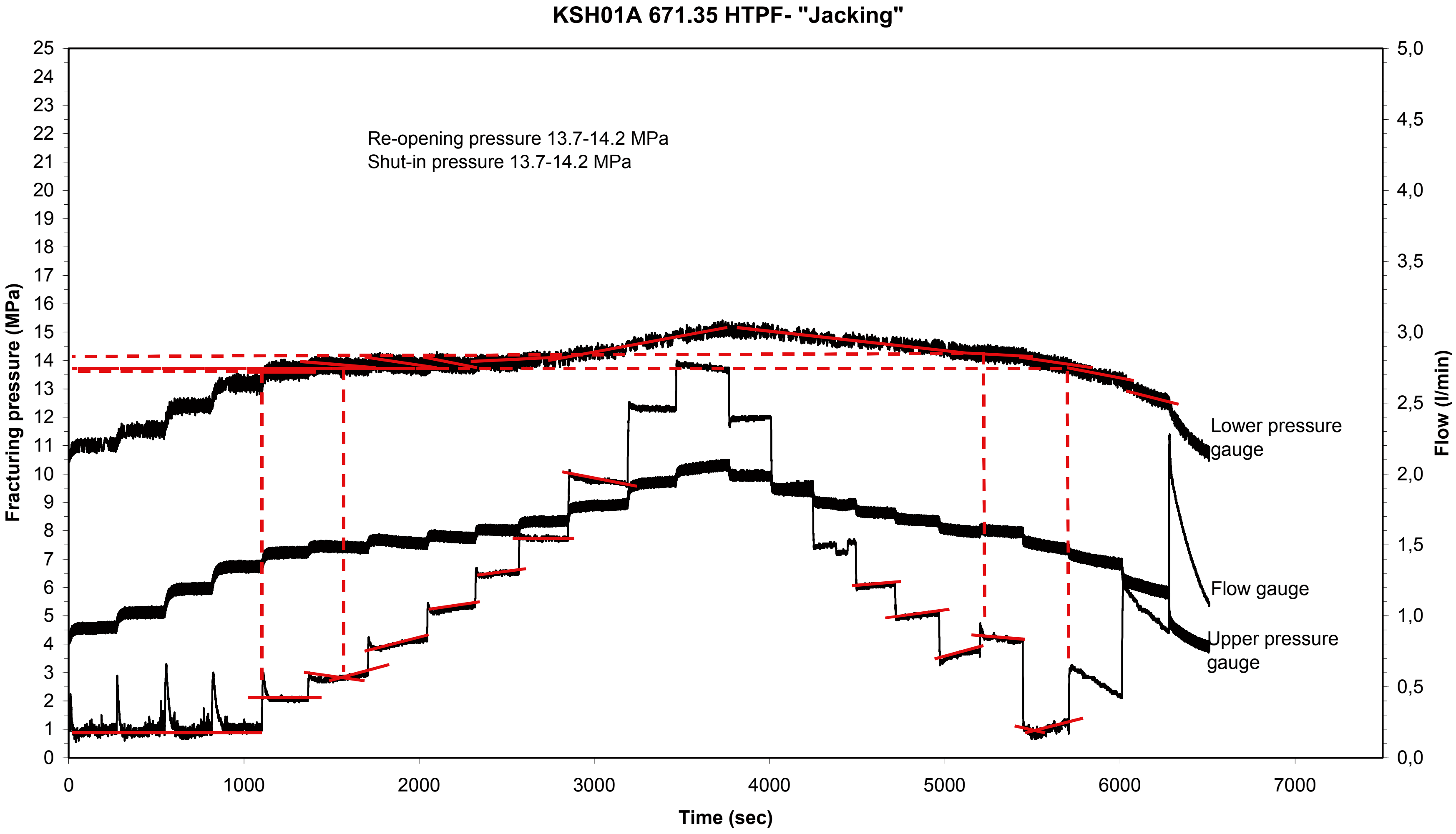


Figure B40. *Shut-in pressure determined from jacking test (HTPF) at 671.35 m borehole length.*

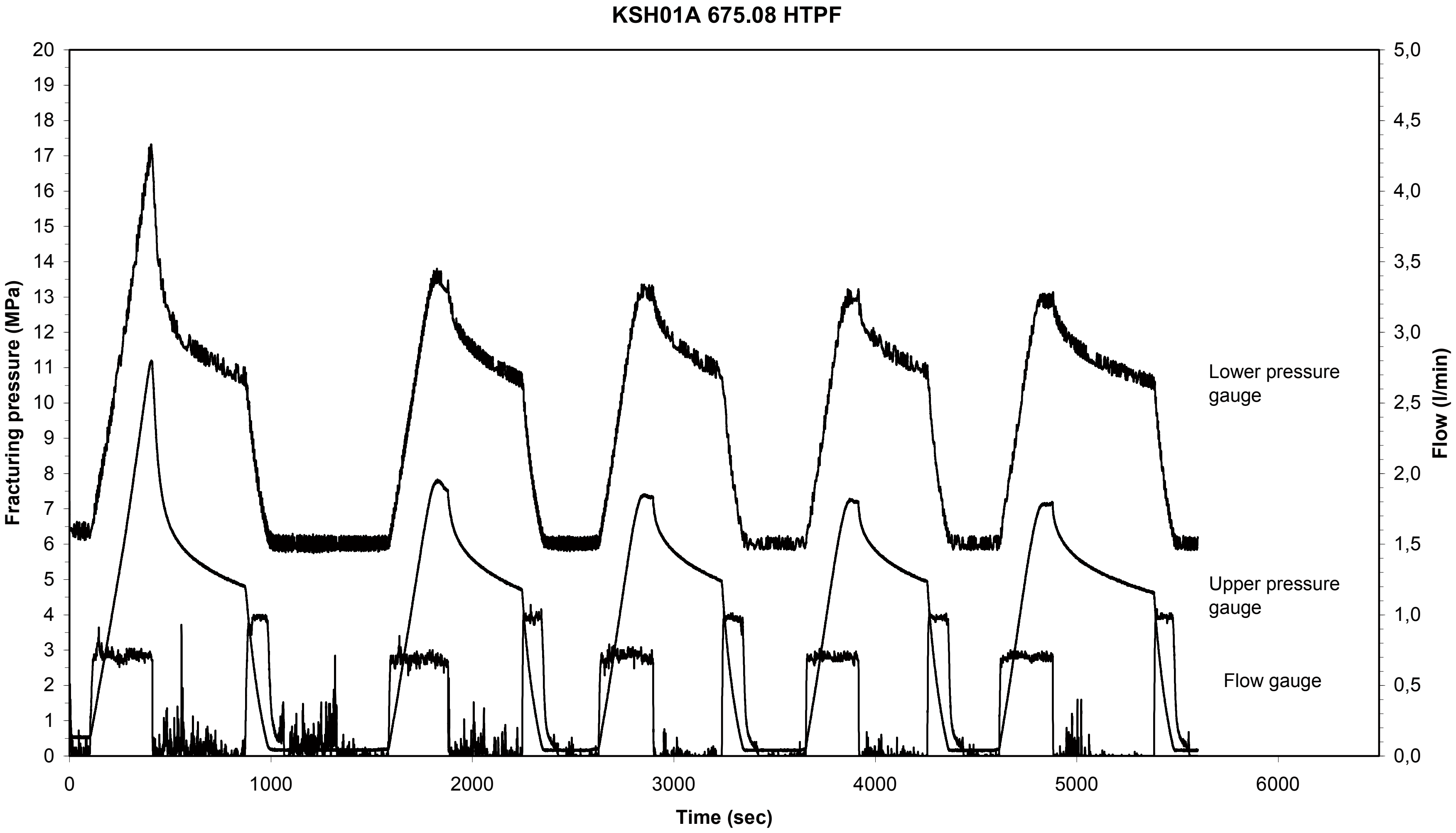


Figure B41. *Pressure and flow record during HTPF tests at 675.08 m borehole length.*

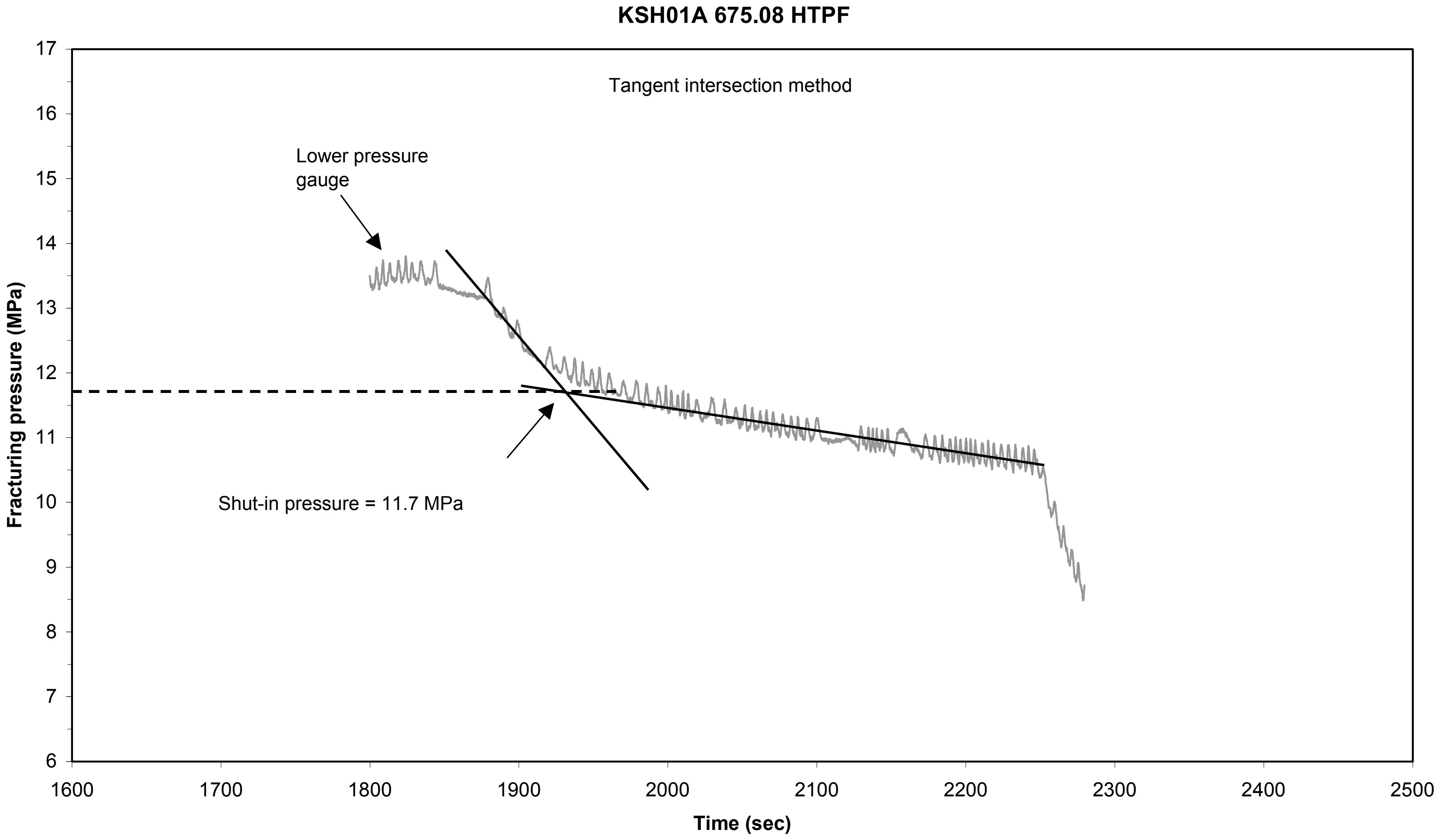


Figure B42. *Shut-in pressure determined with tangent intersection method from HTPF at 675.08 m borehole length.*

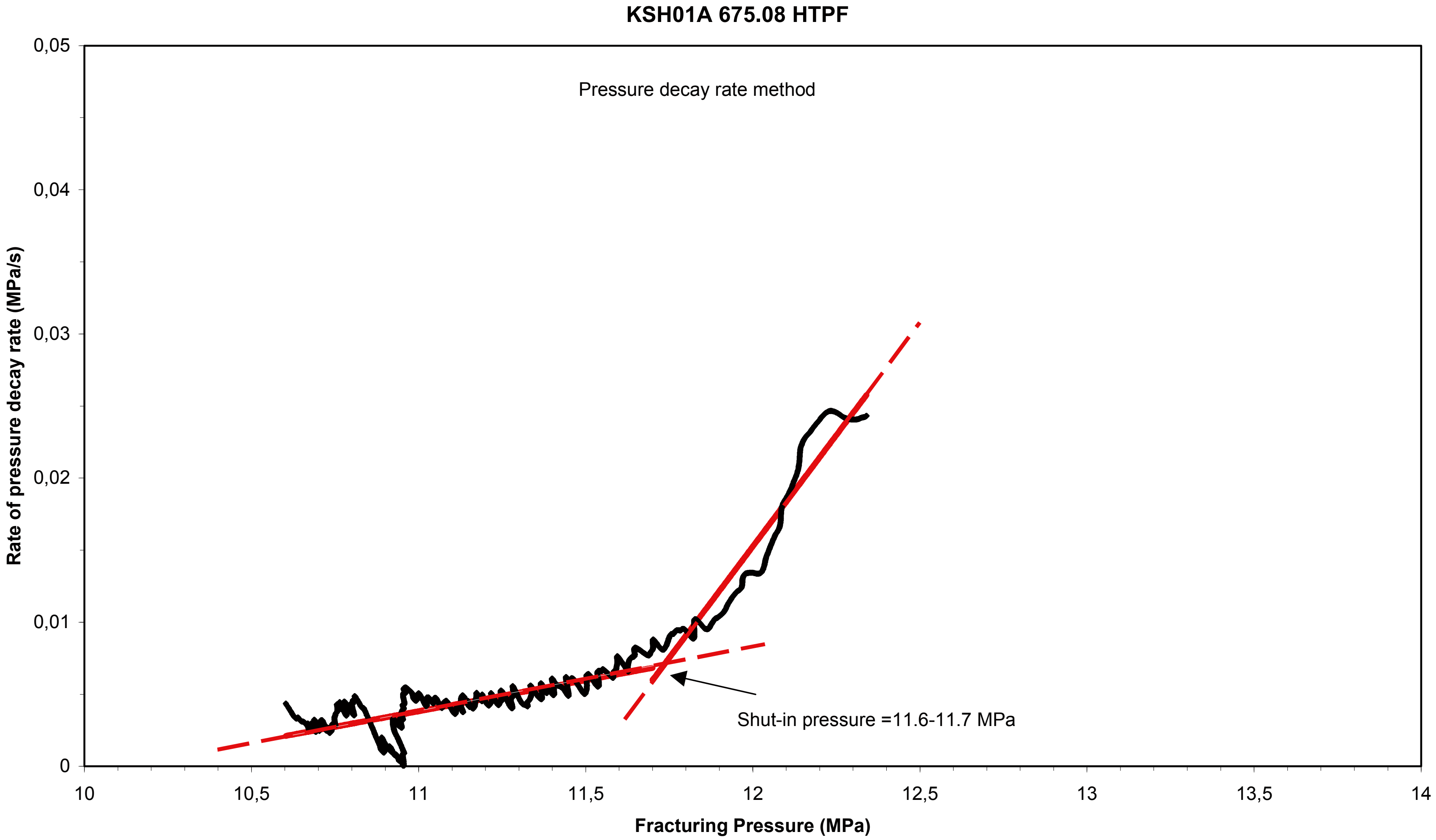


Figure B43. *Shut-in pressure determined by the decay rate method from HTPF at 675.08 m borehole length.*

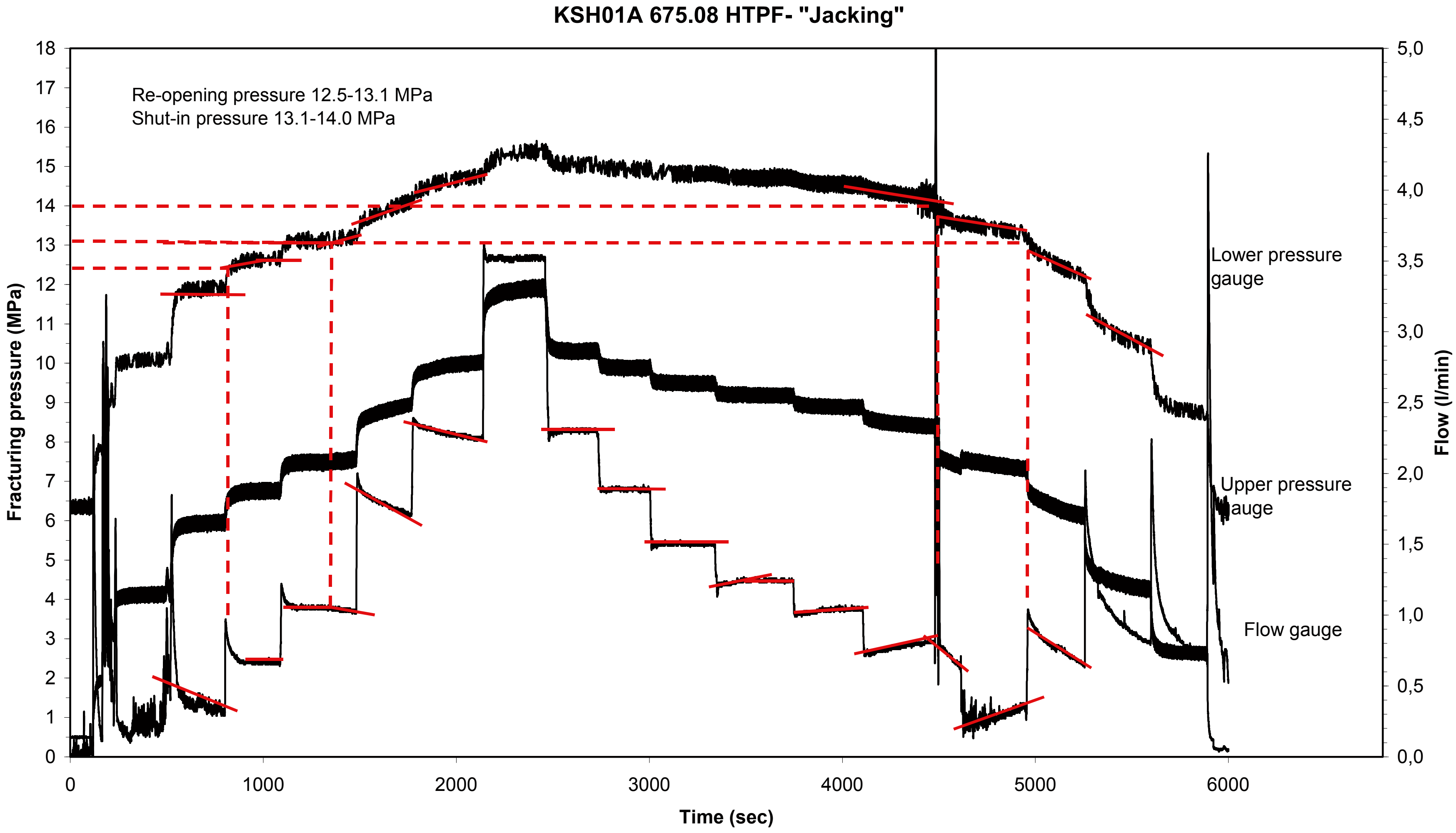


Figure B44. *Shut-in pressure determined from jacking test (HTPF) at 675.08 m borehole length.*

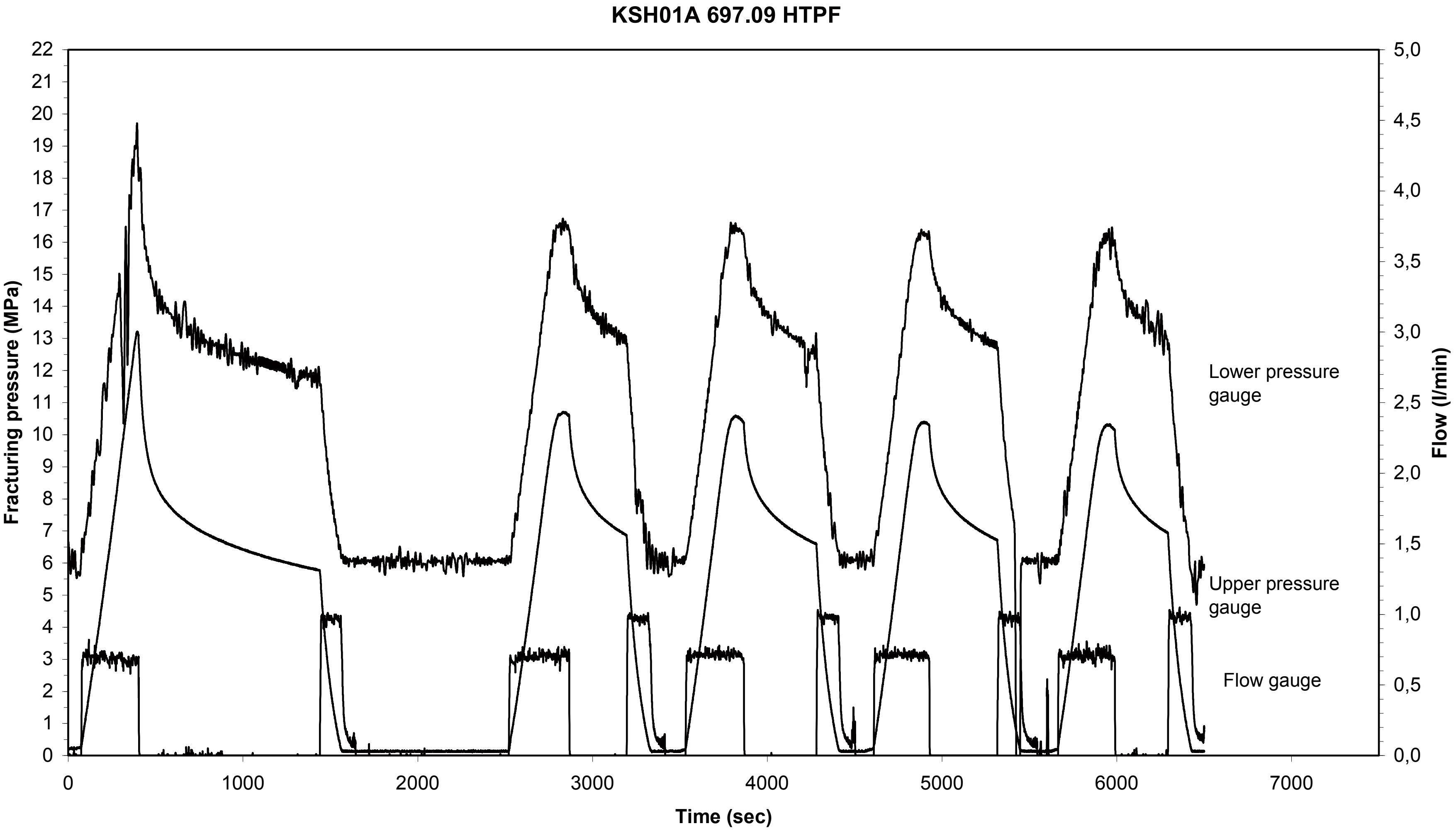


Figure B45. *Pressure and flow record during HTPF tests at 697.09 m borehole length.*

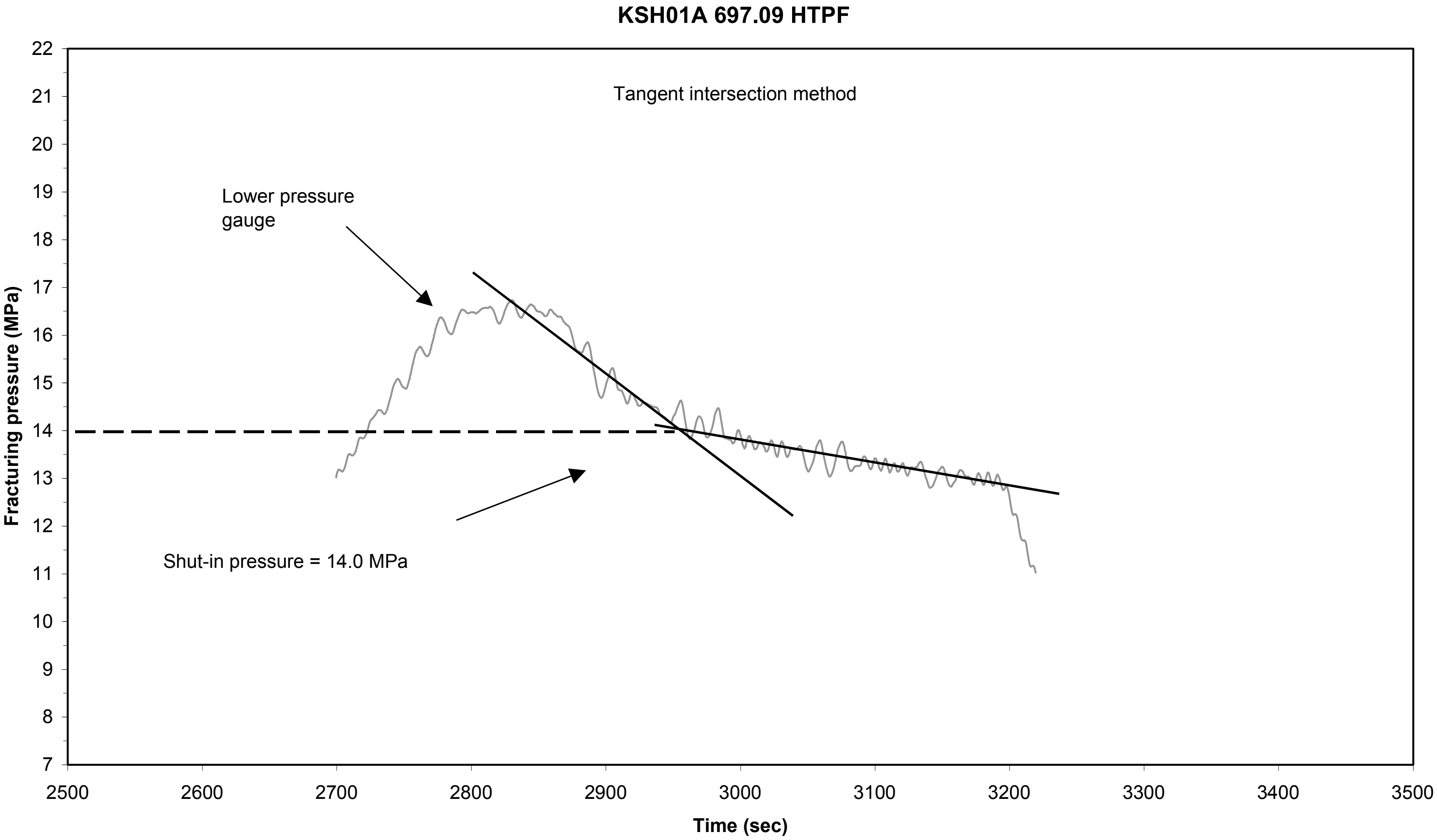


Figure B46. *Shut-in pressure determined with tangent intersection method from HTPF at 697.09 m borehole length.*

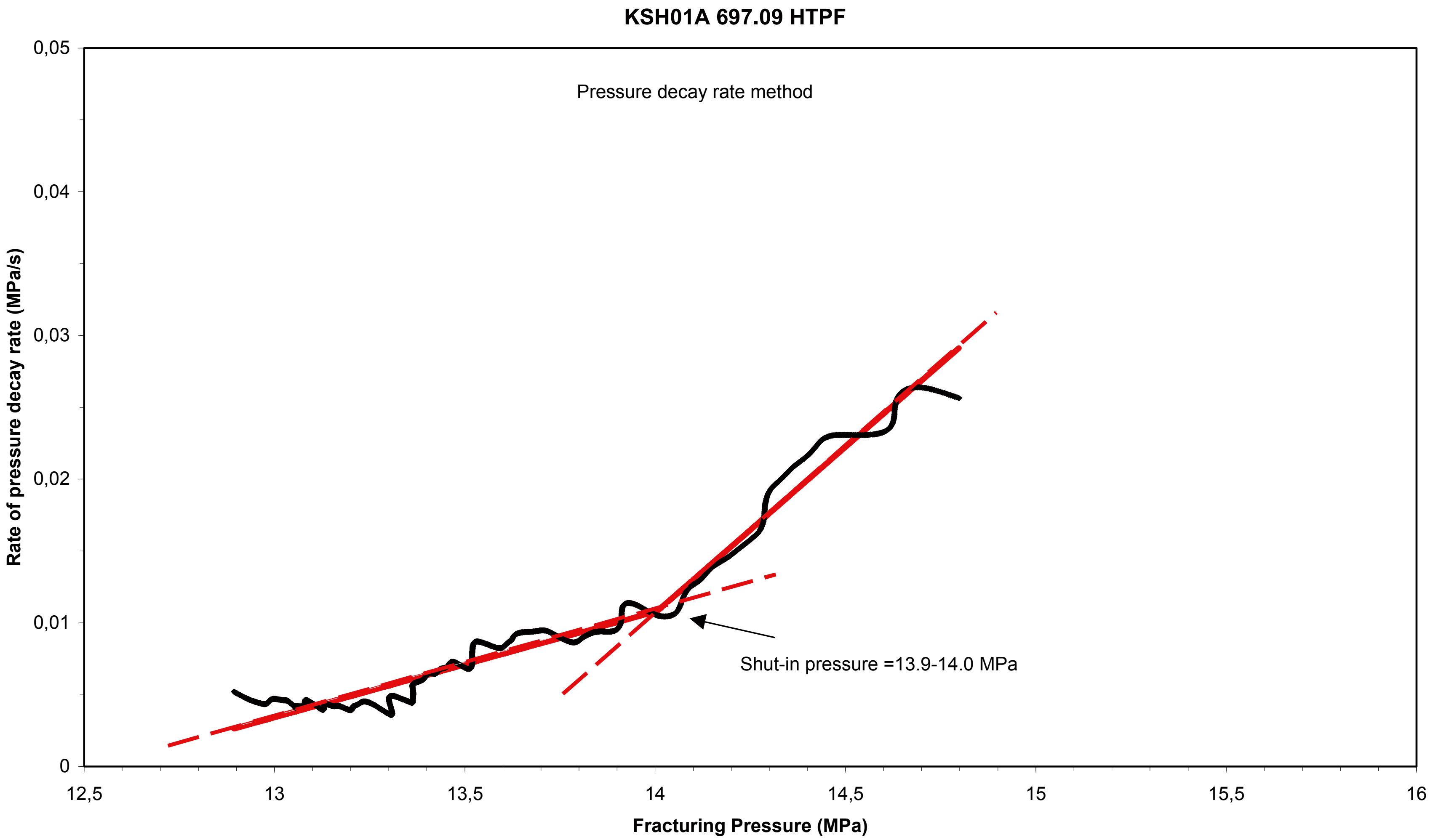


Figure B47. *Shut-in pressure determined by the decay rate method from HTPF at 697.09 m borehole length.*

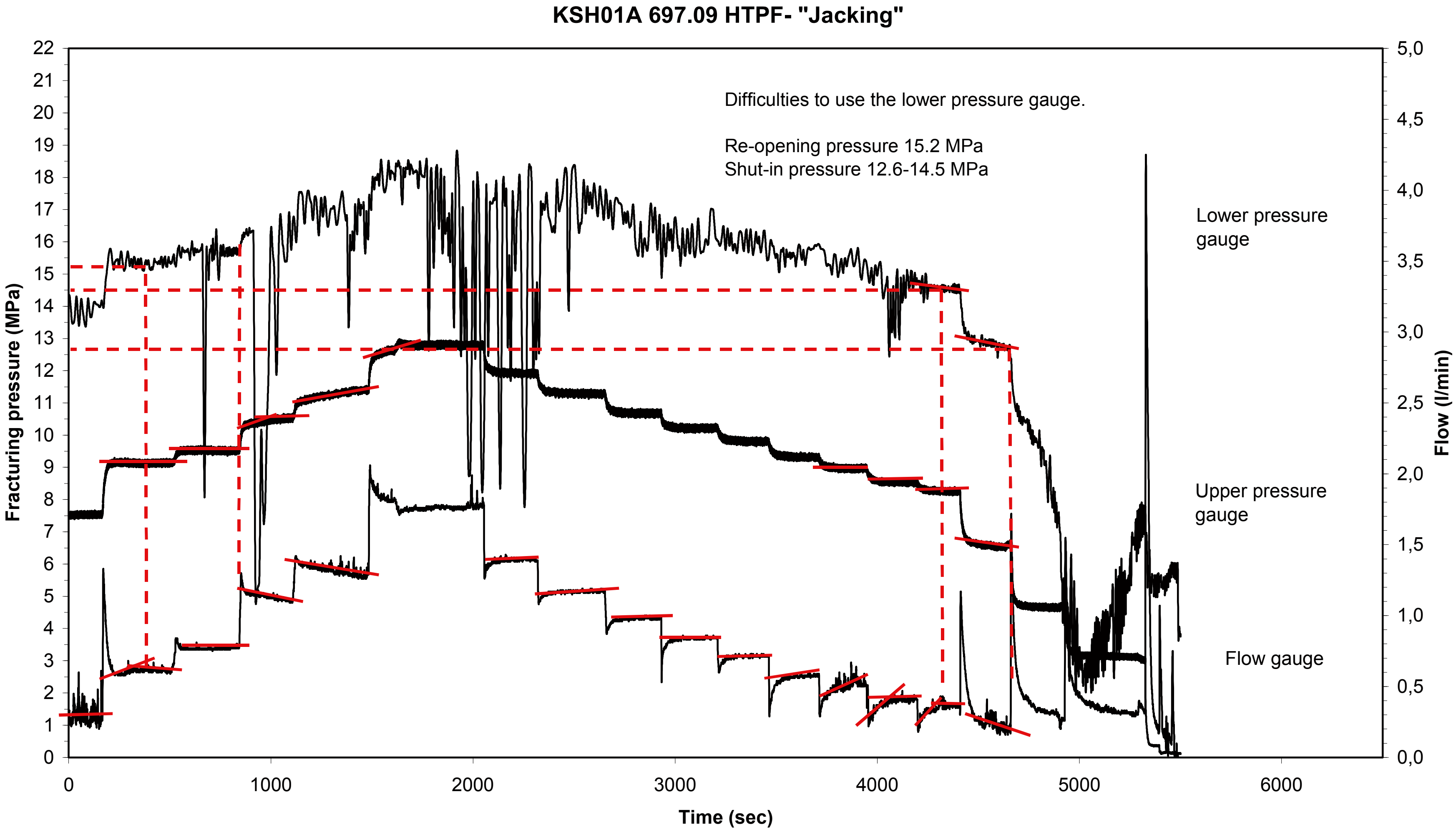


Figure B48. *Shut-in pressure determined from jacking test (HTPF) at 697.09 m borehole length.*

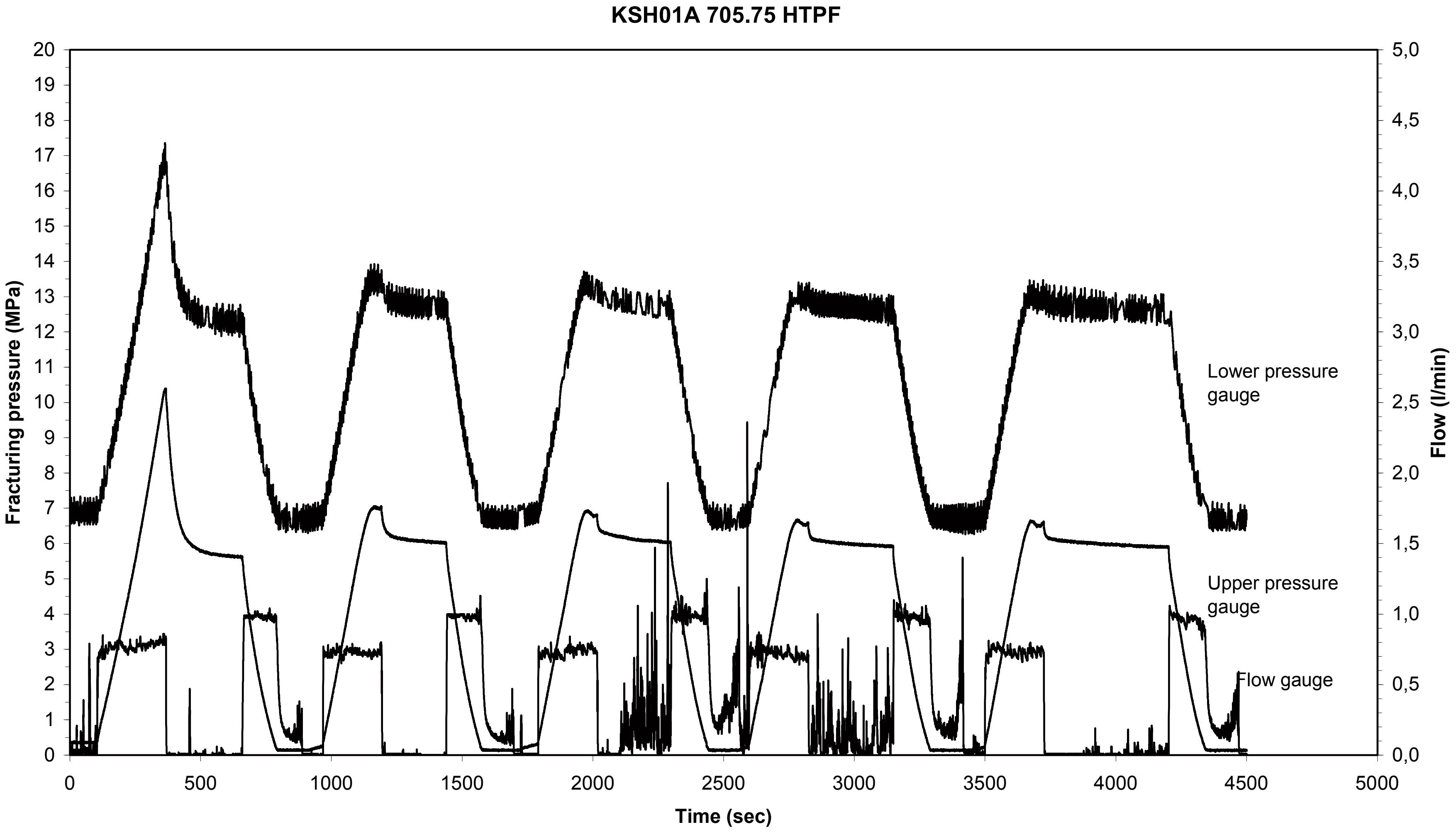


Figure B49. *Pressure and flow record during HTPF tests at 705.75 m borehole length.*

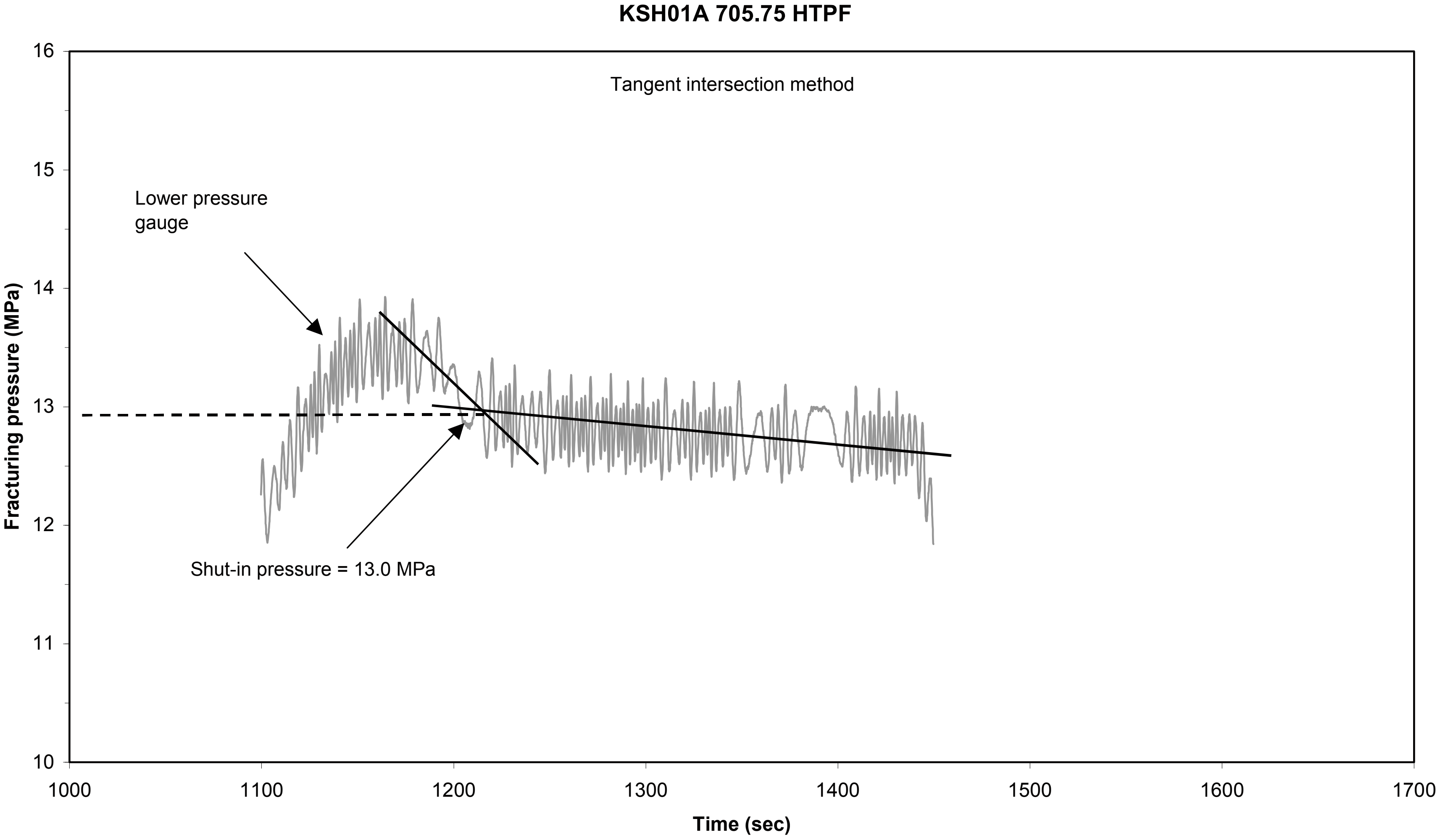


Figure B50. *Shut-in pressure determined with tangent intersection method from HTPF at 705.75 m borehole length.*

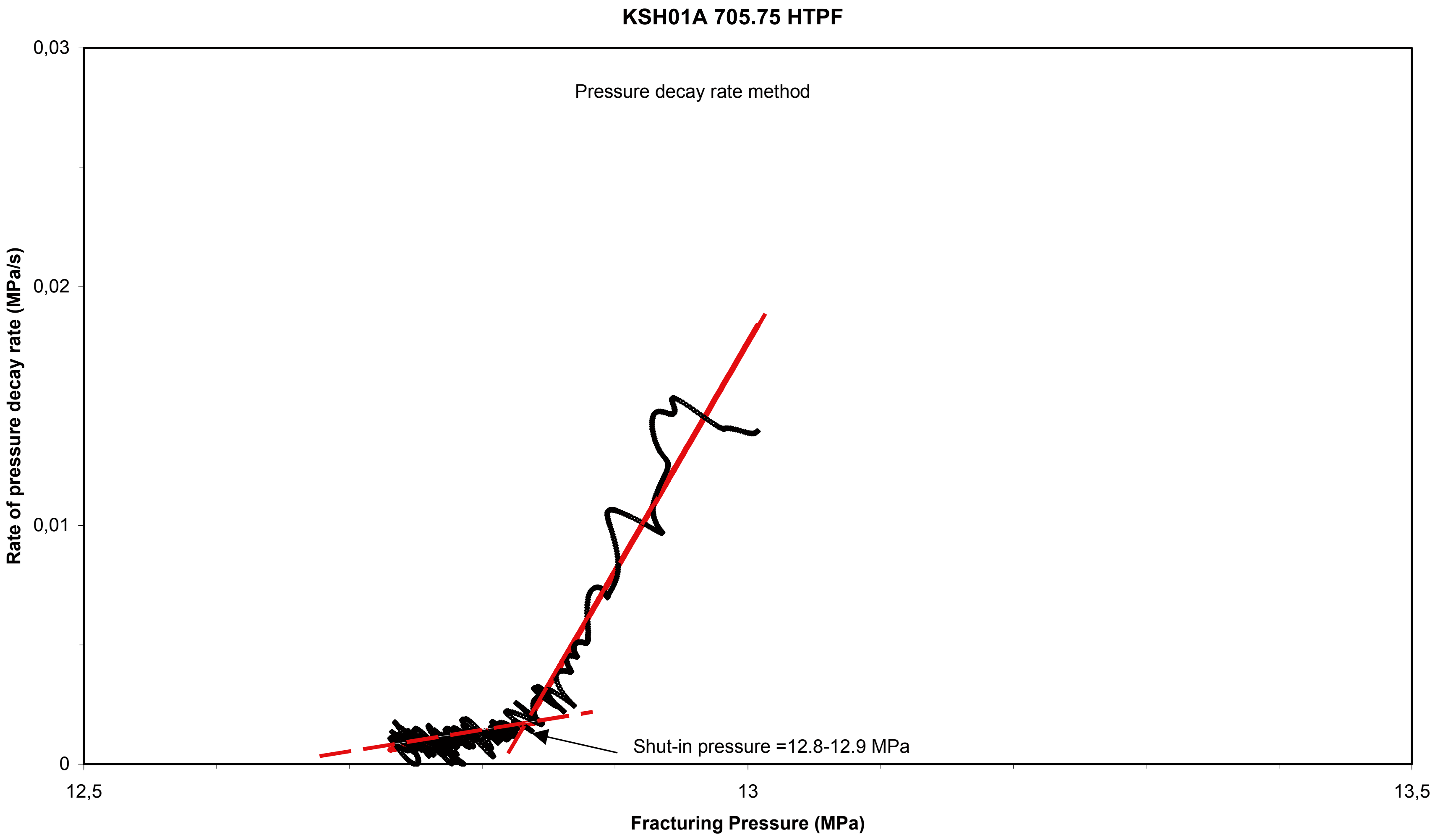


Figure B51. Shut-in pressure determined by the decay rate method from HTPF at 705.75 m borehole length.

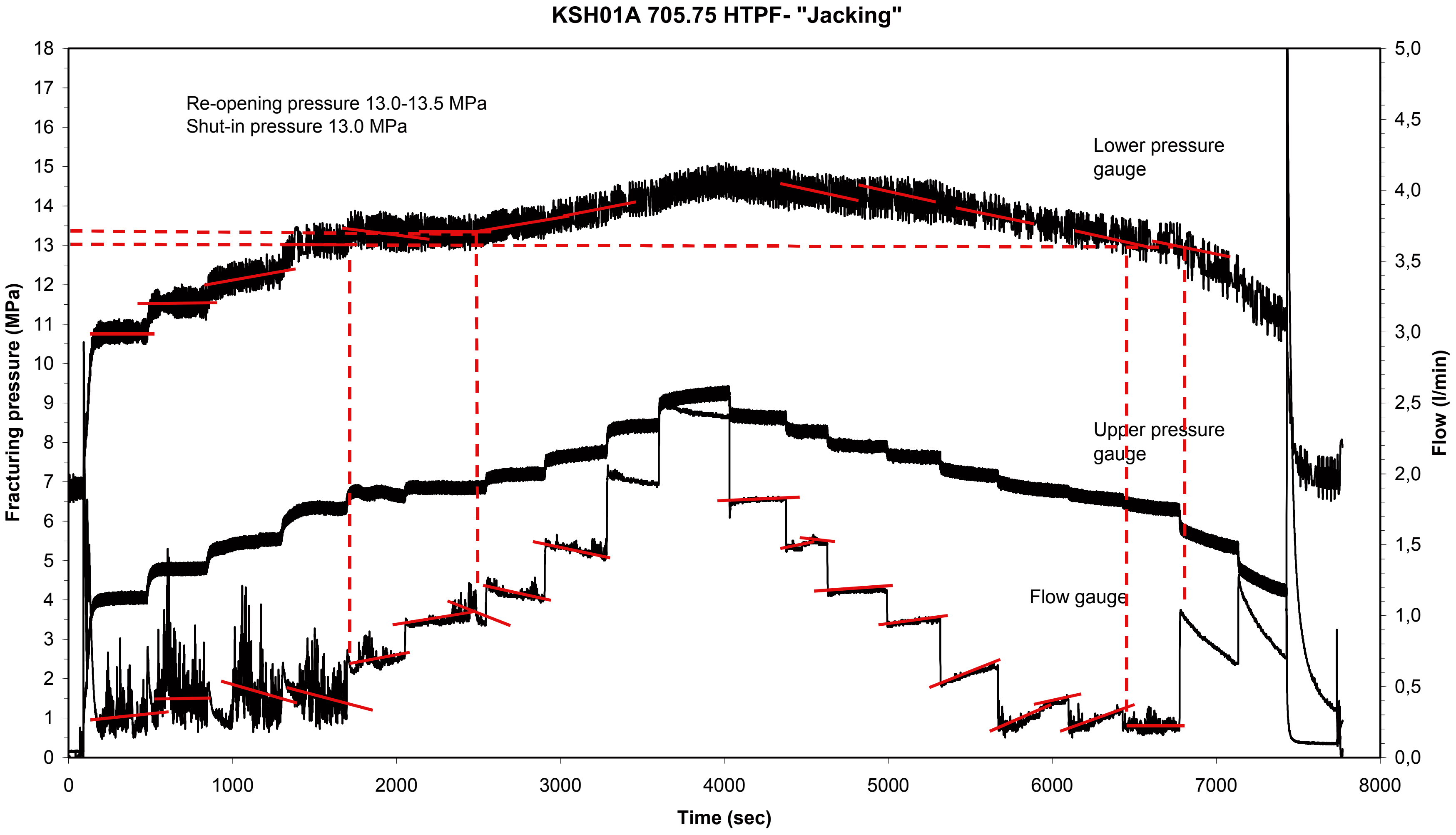


Figure B52. *Shut-in pressure determined from jacking test (HTPF) at 705.75 m borehole length.*

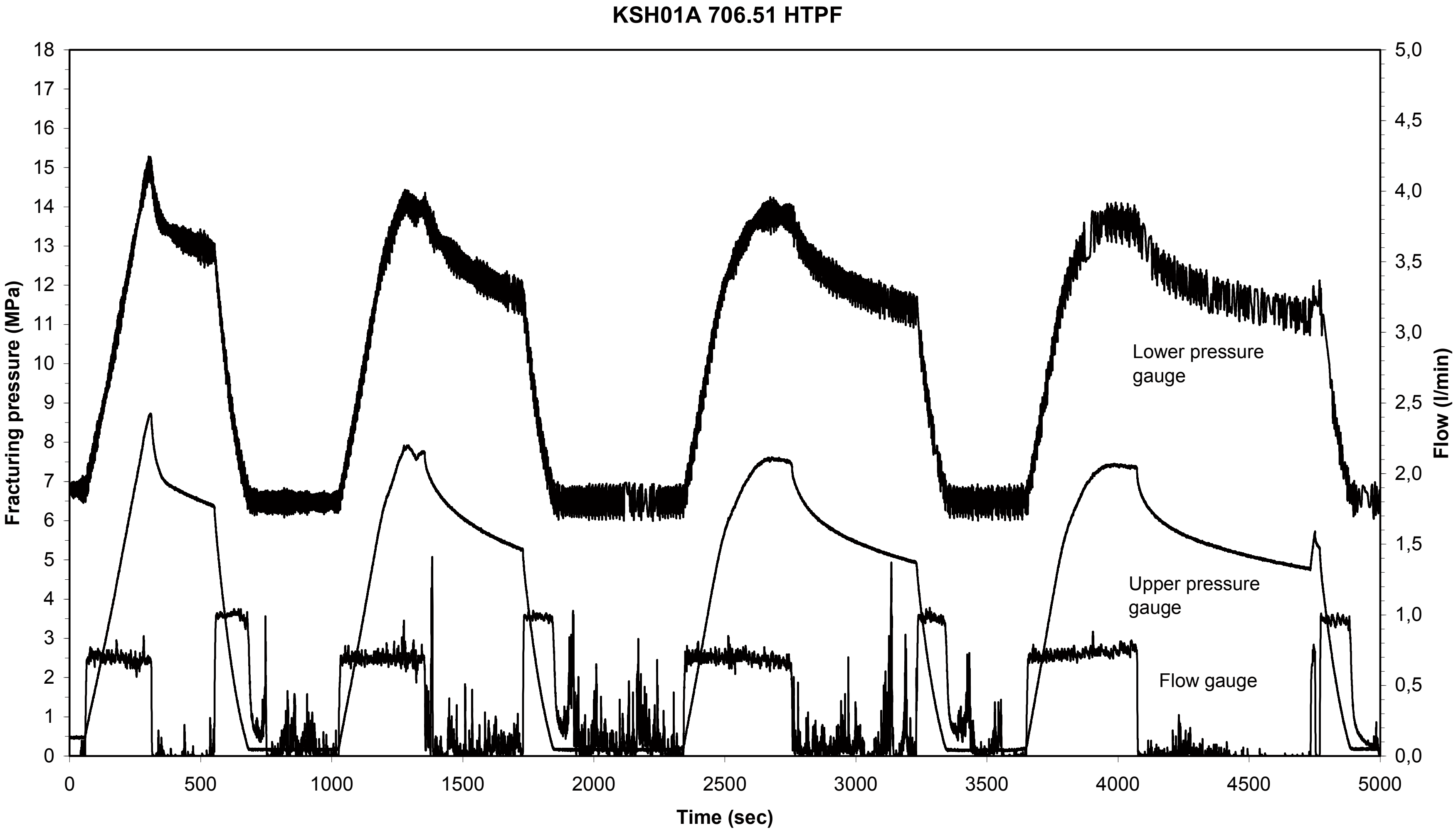


Figure B53. *Pressure and flow record during HTPF tests at 706.51 m borehole length.*

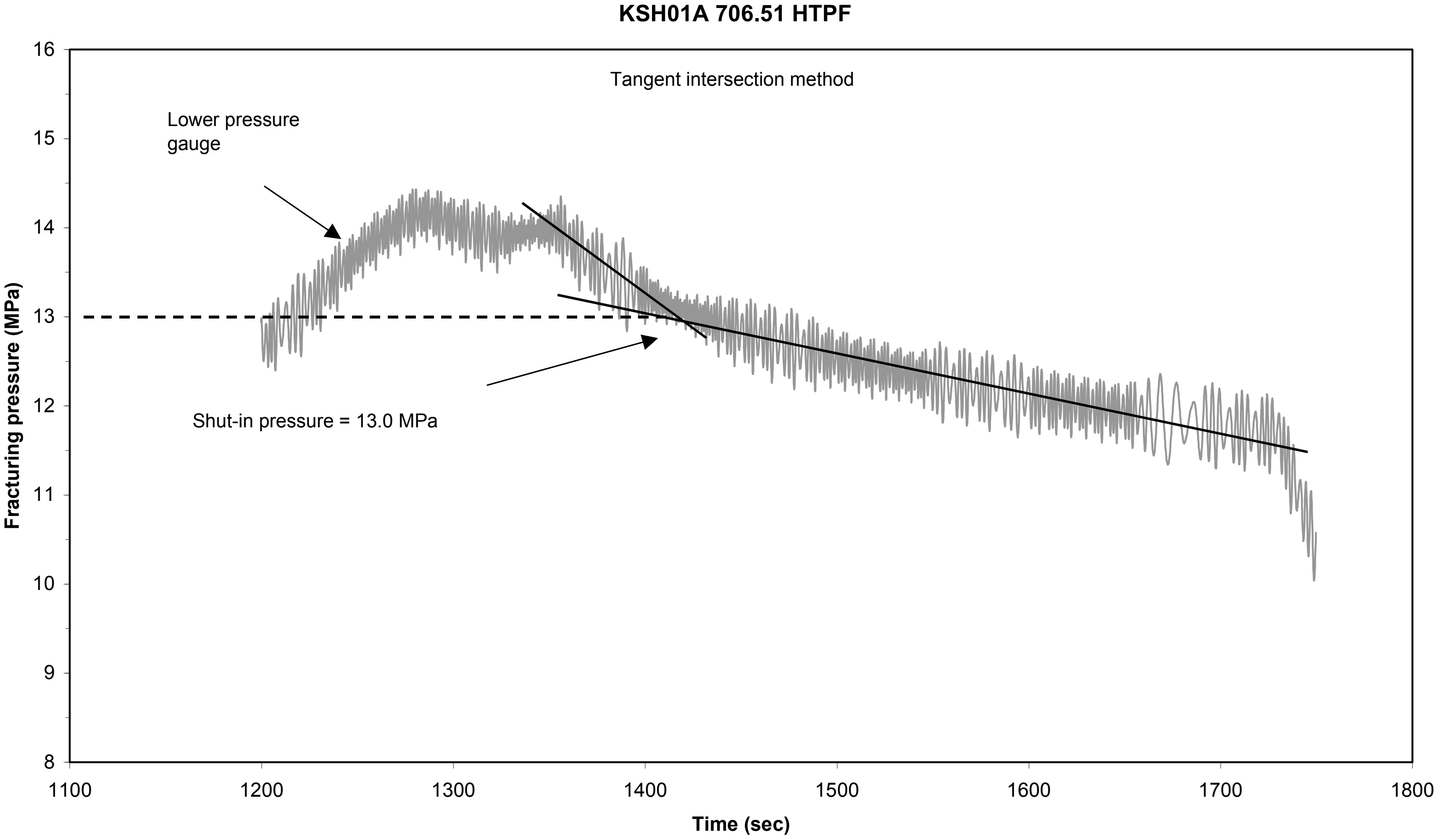


__Figure B54.__ Shut-in pressure determined with tangent intersection method from HTPF at 706.51 m borehole length.

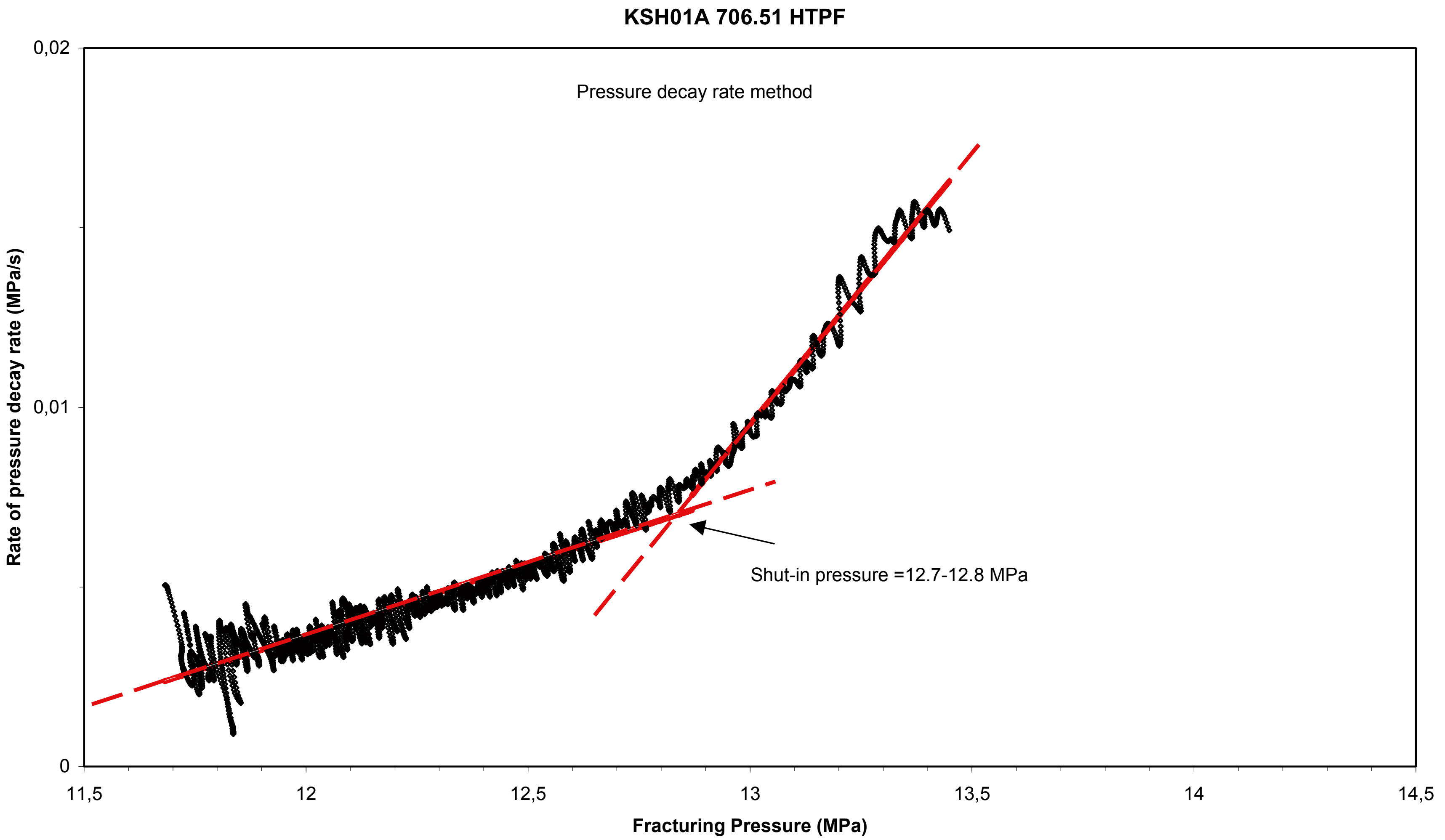


Figure B55. *Shut-in pressure determined by the decay rate method from HTPF at 706.51 m borehole length.*

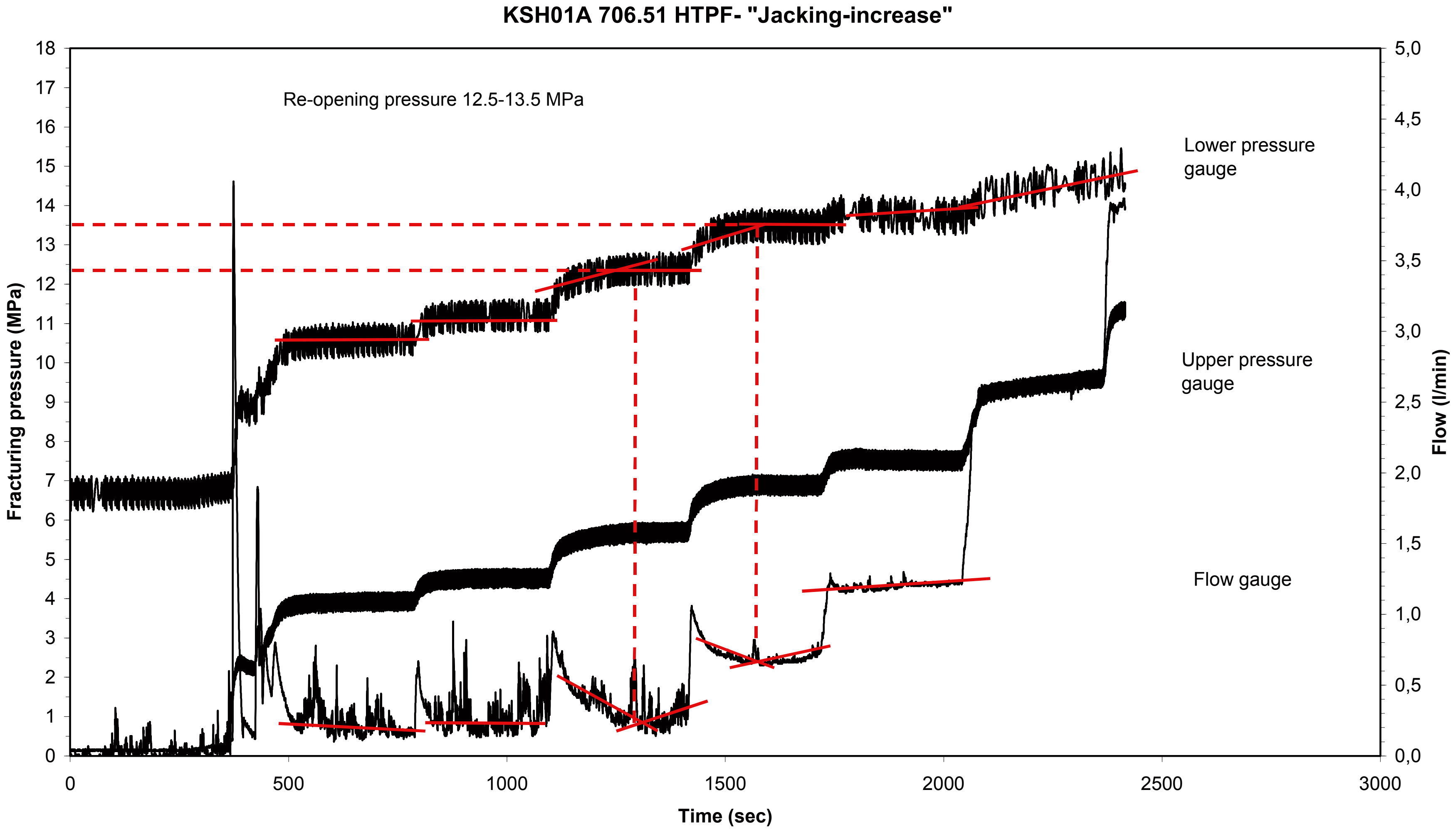


Figure B56a. *Shut-in pressure determined from jacking test (HTPF) at 706.51 m borehole length. Stepwise increasing flow only.*

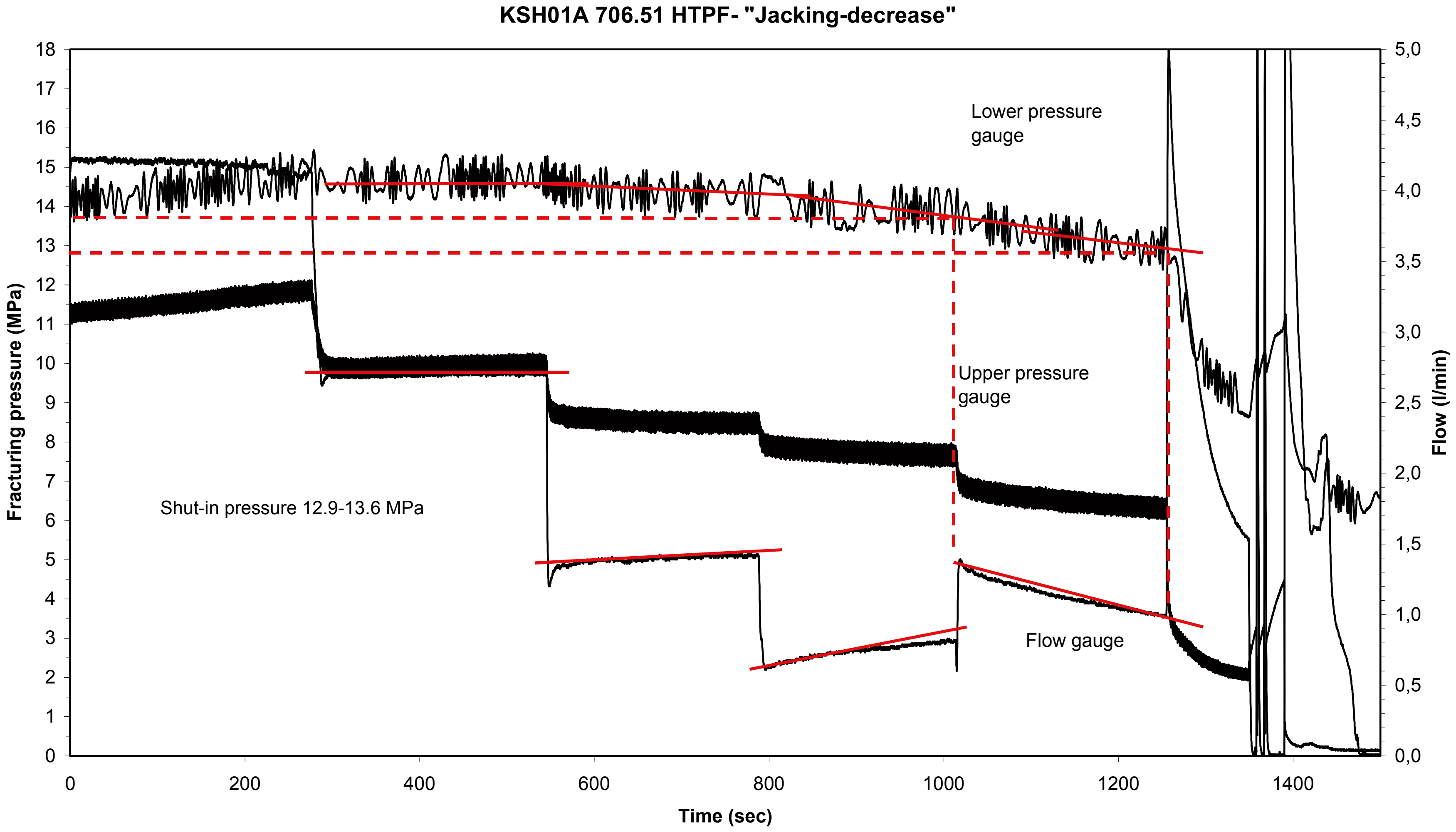


Figure B57b. Shut-in pressure determined from jacking test (HTPF) at 706.51 m borehole length. Stepwise decreasing flow only.

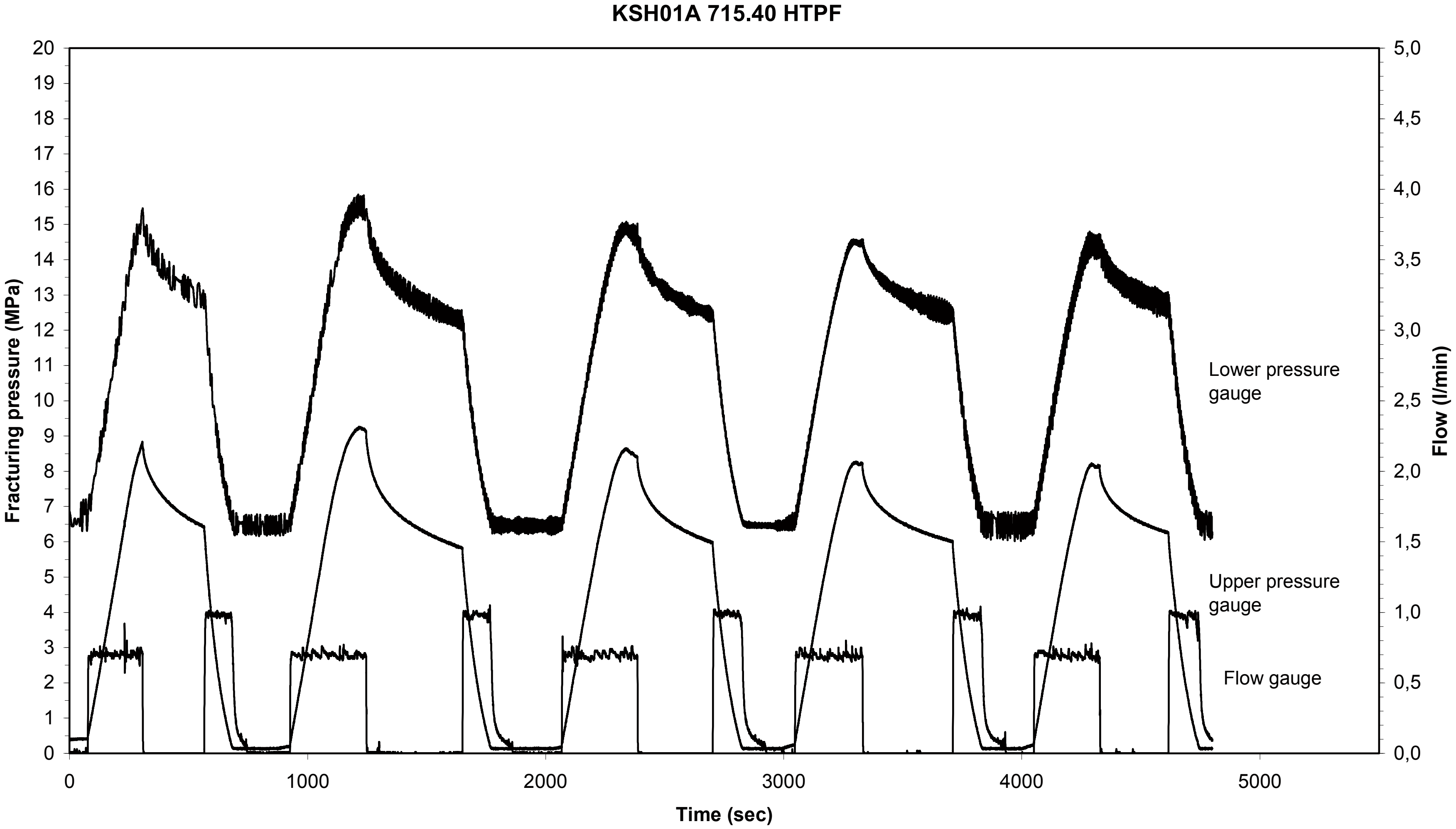


Figure B58. *Pressure and flow record during HTPF tests at 715.40 m borehole length.*

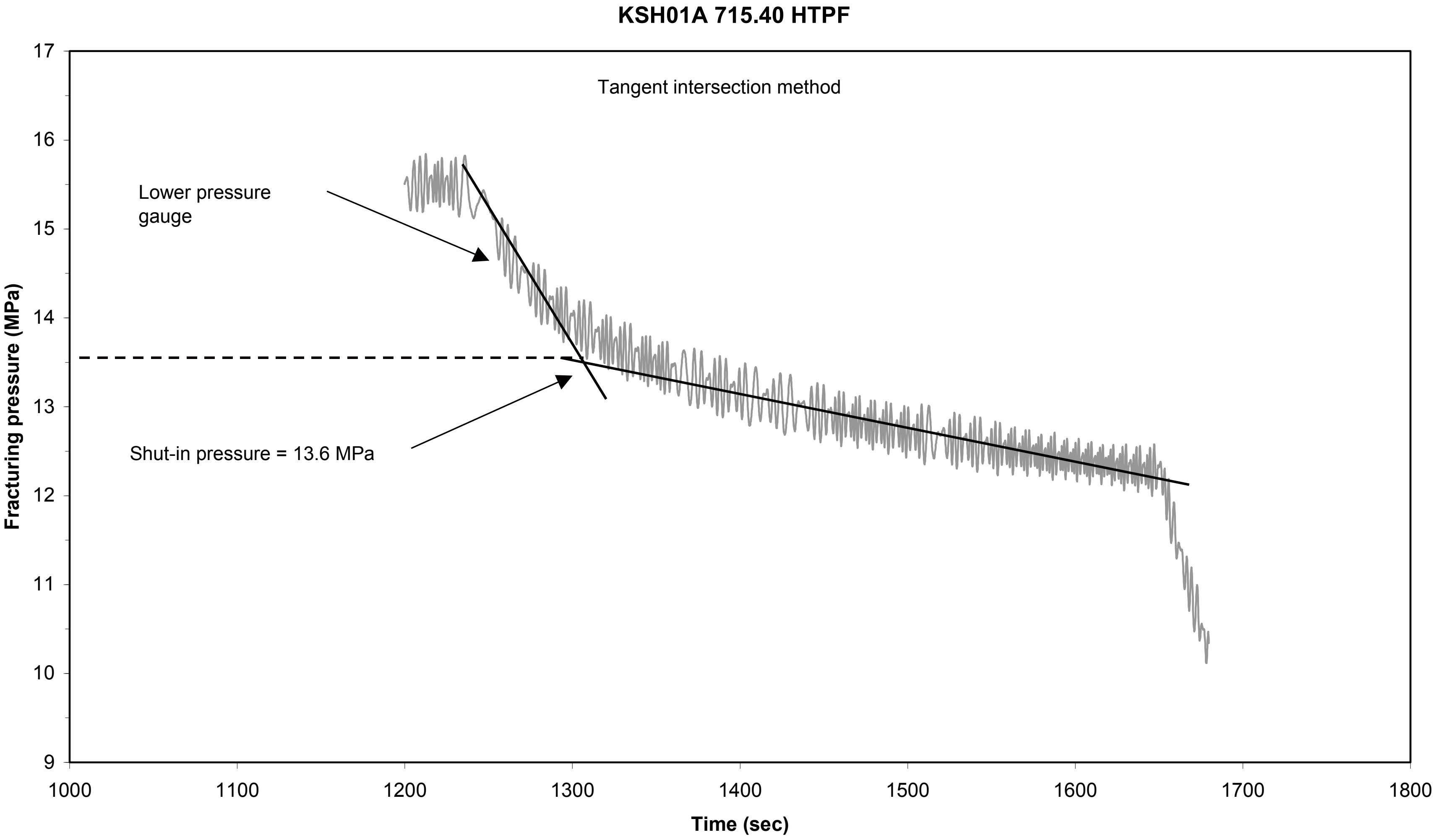


Figure B59. *Shut-in pressure determined with tangent intersection method from HTPF at 715.40 m borehole length.*

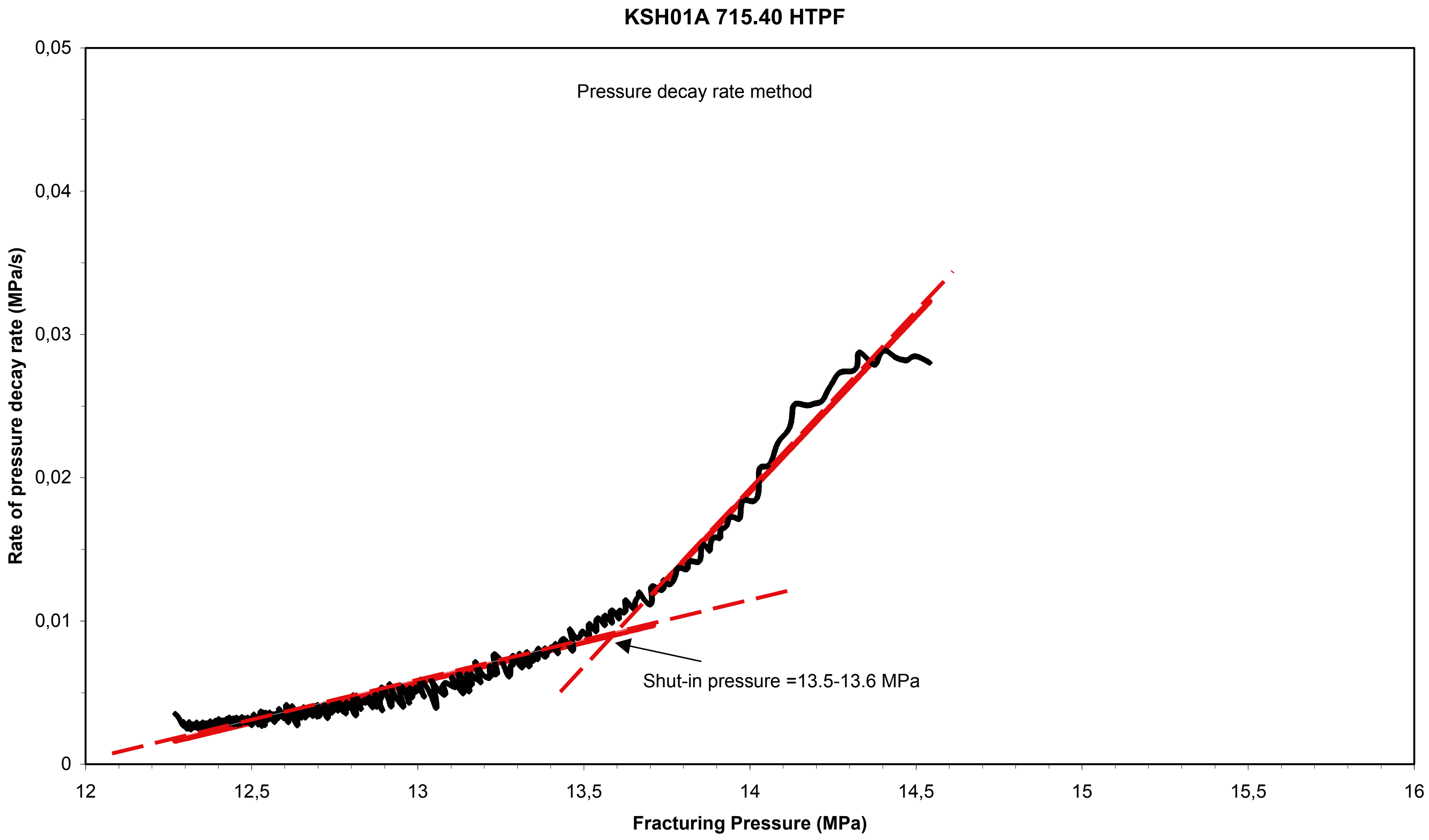


Figure B60. *Shut-in pressure determined by the decay rate method from HTPF at 715.40 m borehole length.*

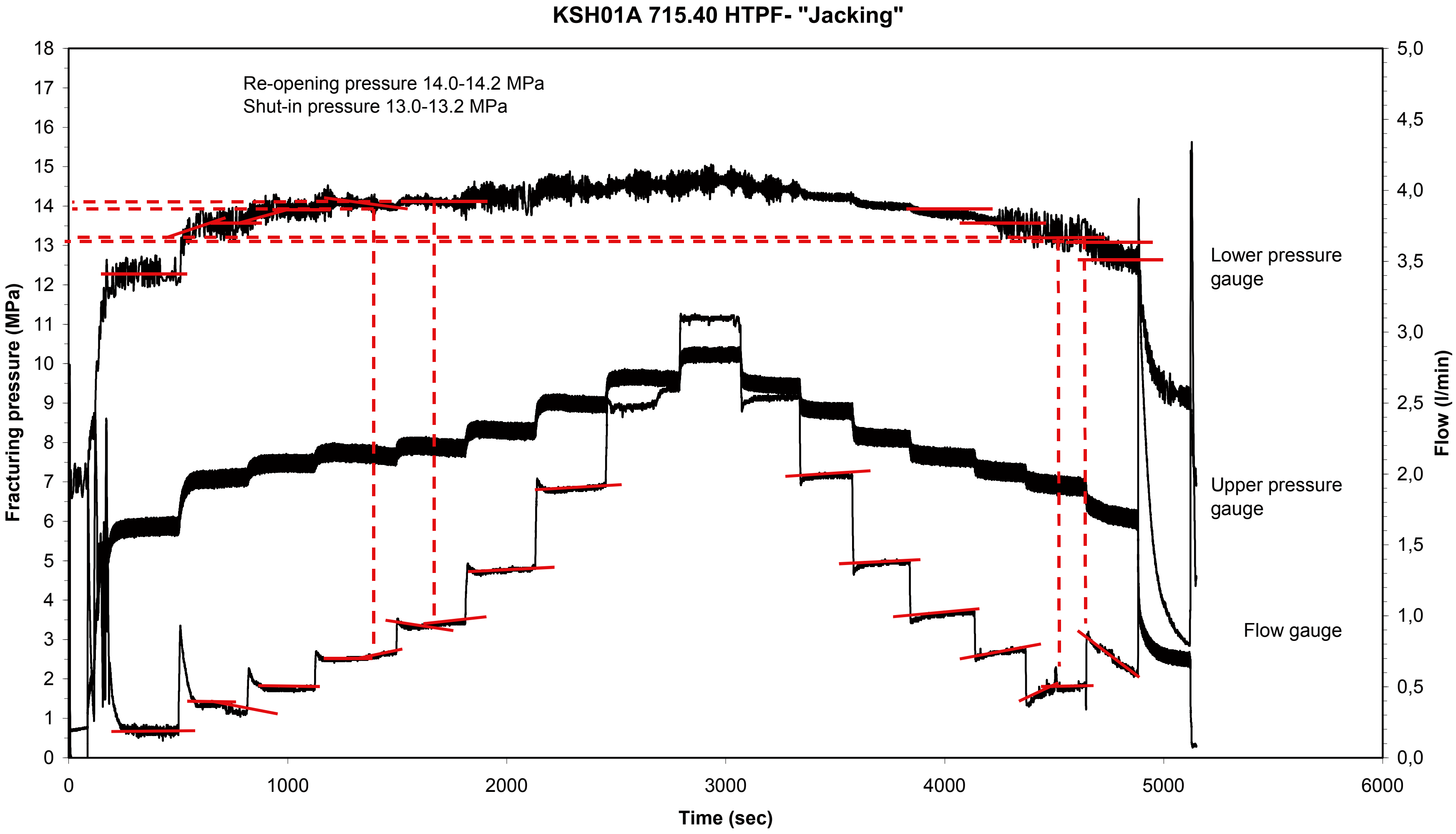


Figure B61. *Shut-in pressure determined from jacking test (HTPF) at 715.40 m borehole length.*

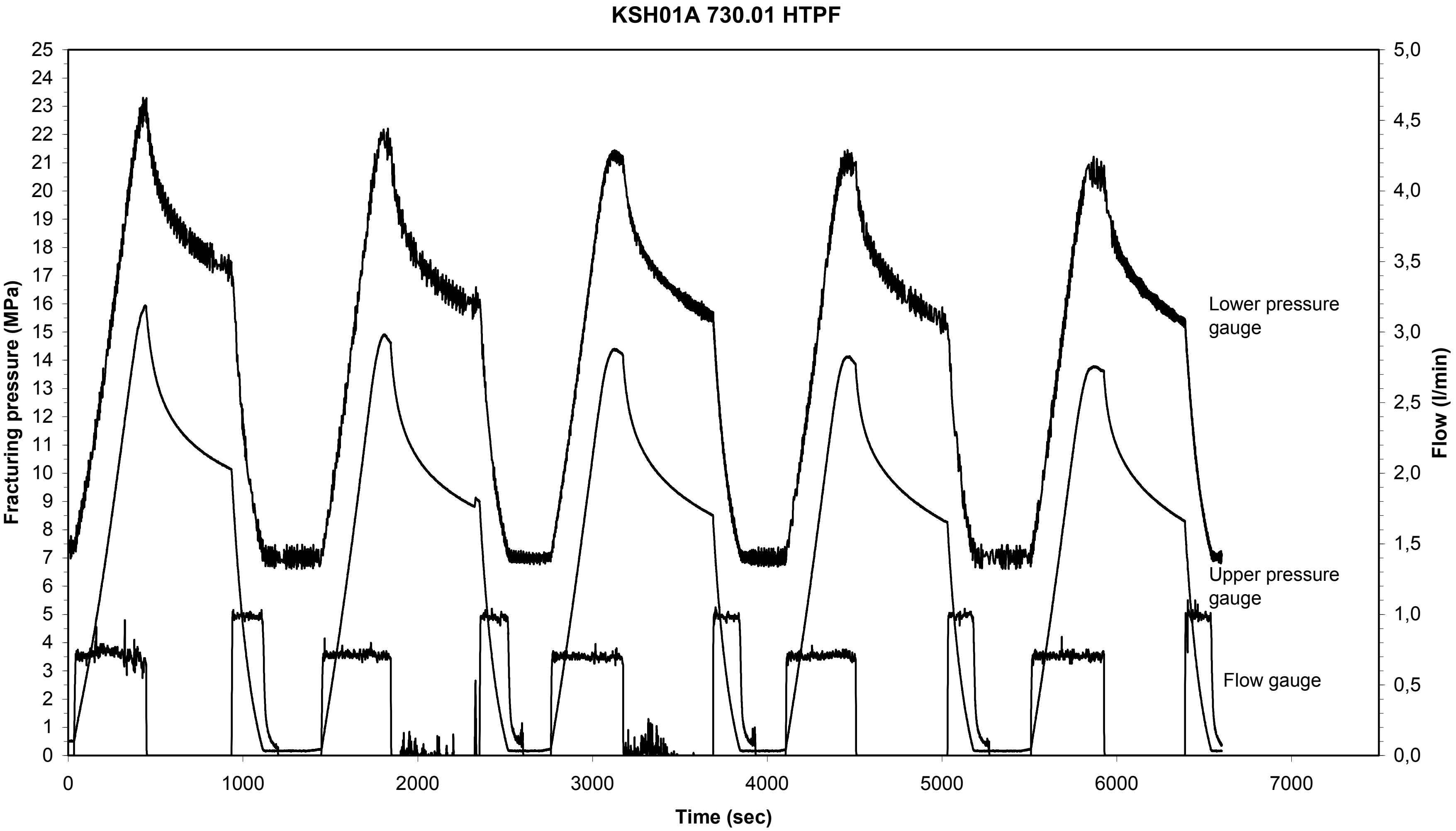


Figure B62. *Pressure and flow record during HTPF tests at 730.01 m borehole length.*

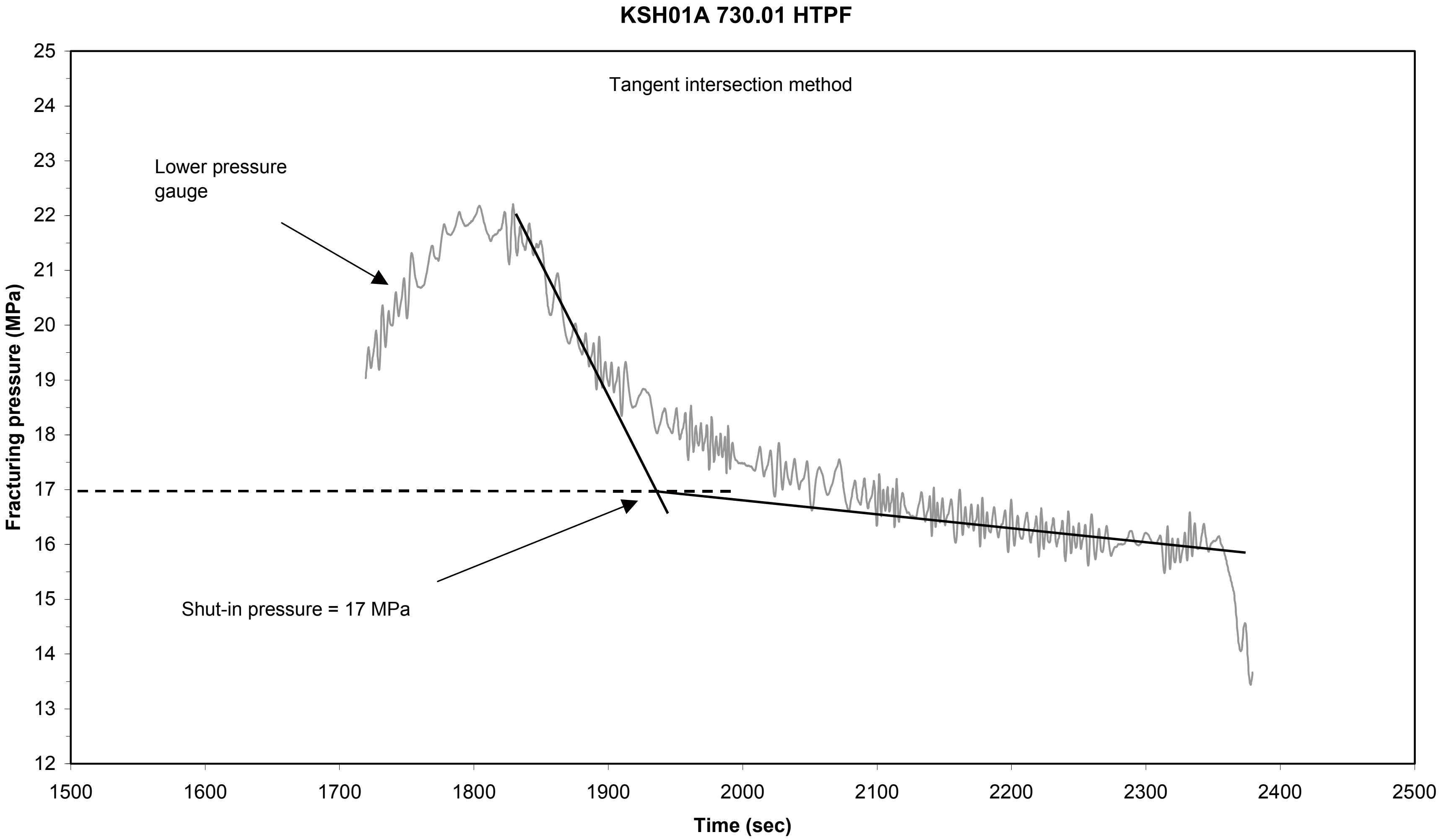


***Figure B63.** Shut-in pressure determined with tangent intersection method from HTPF at 730.01 m borehole length.*

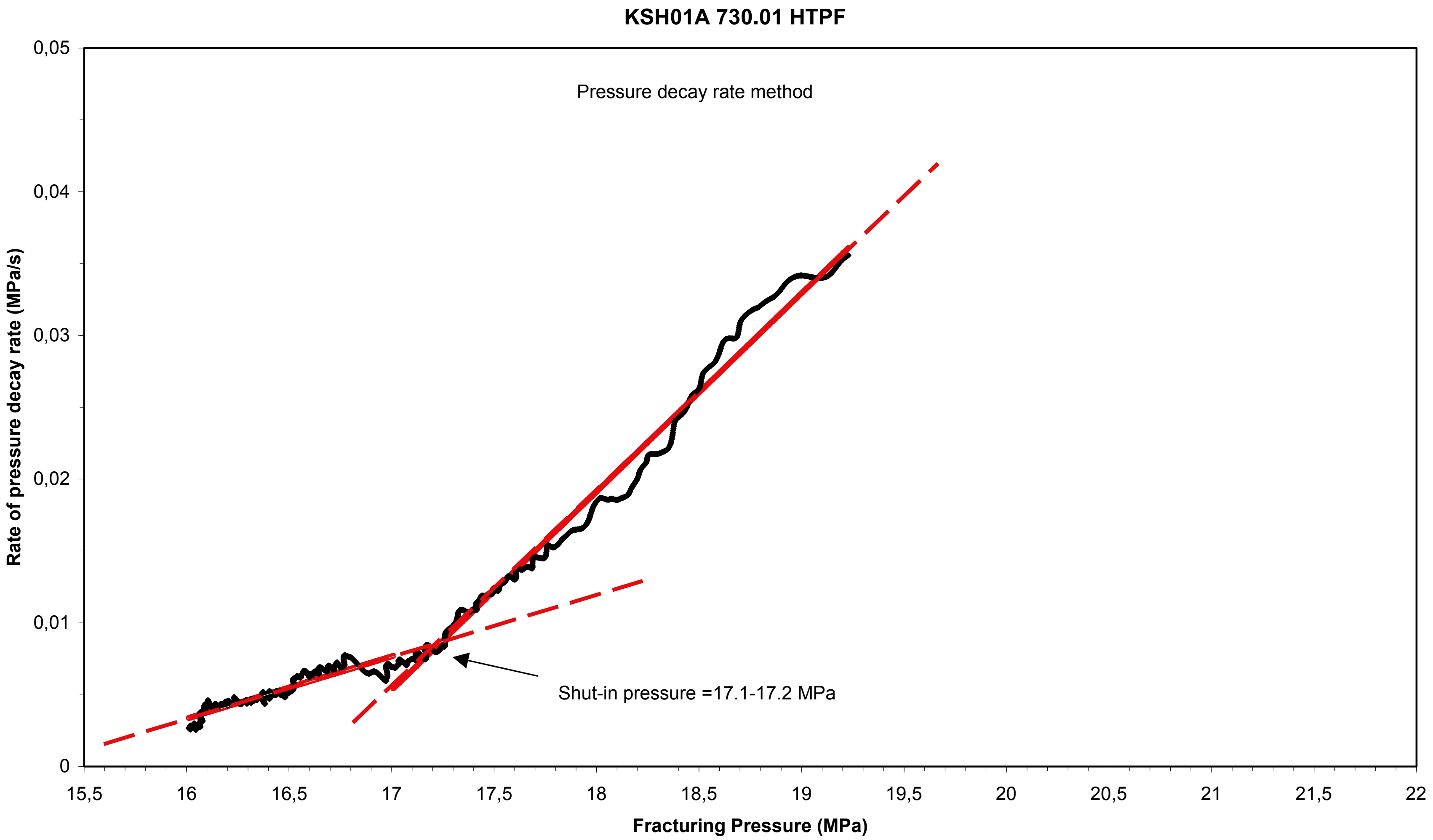


Figure B64. *Shut-in pressure determined by the decay rate method from HTPF at 730.01 m borehole length.*

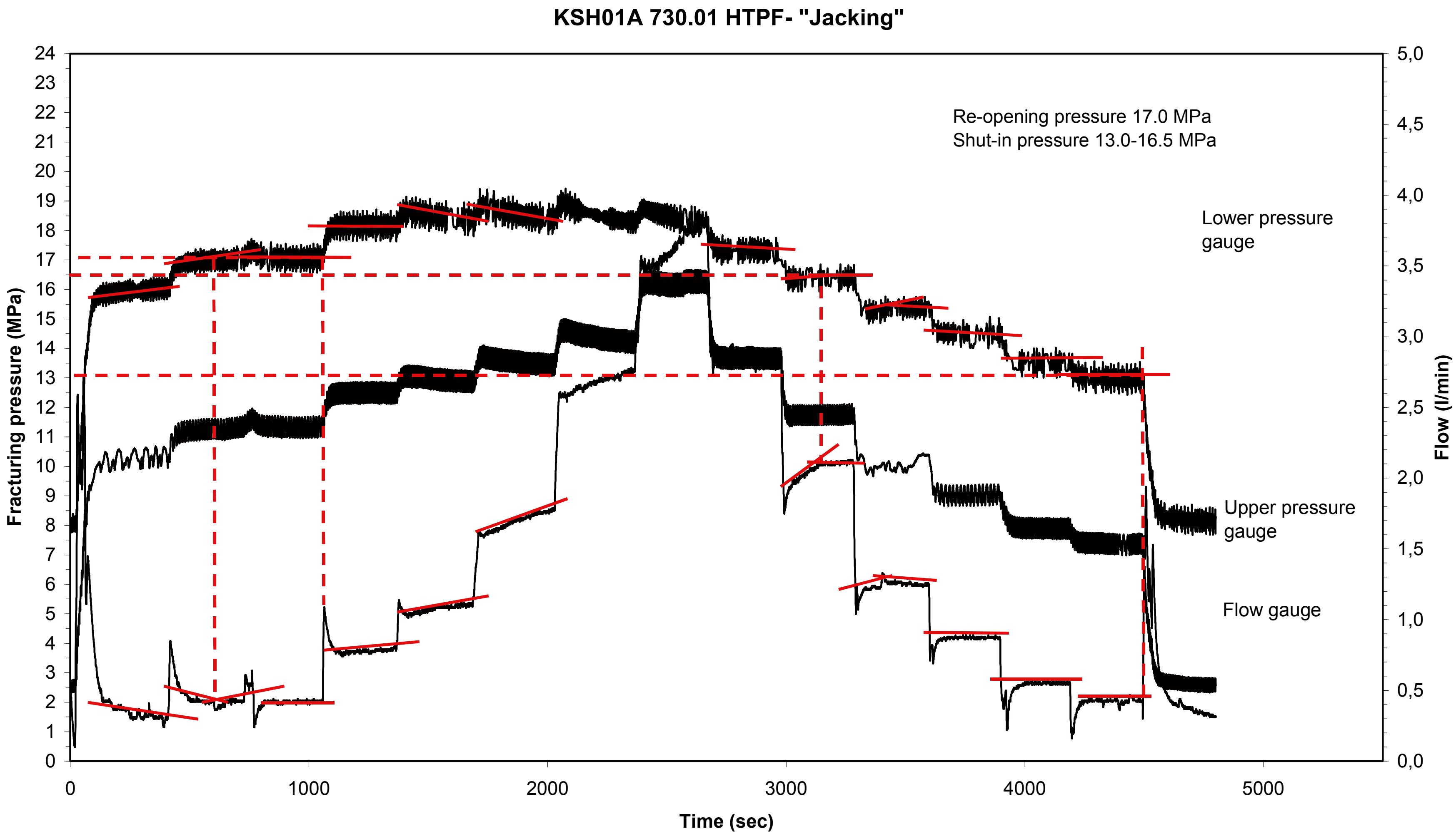


Figure B65. *Shut-in pressure determined from jacking test (HTPF) at 730.01 m borehole length.*

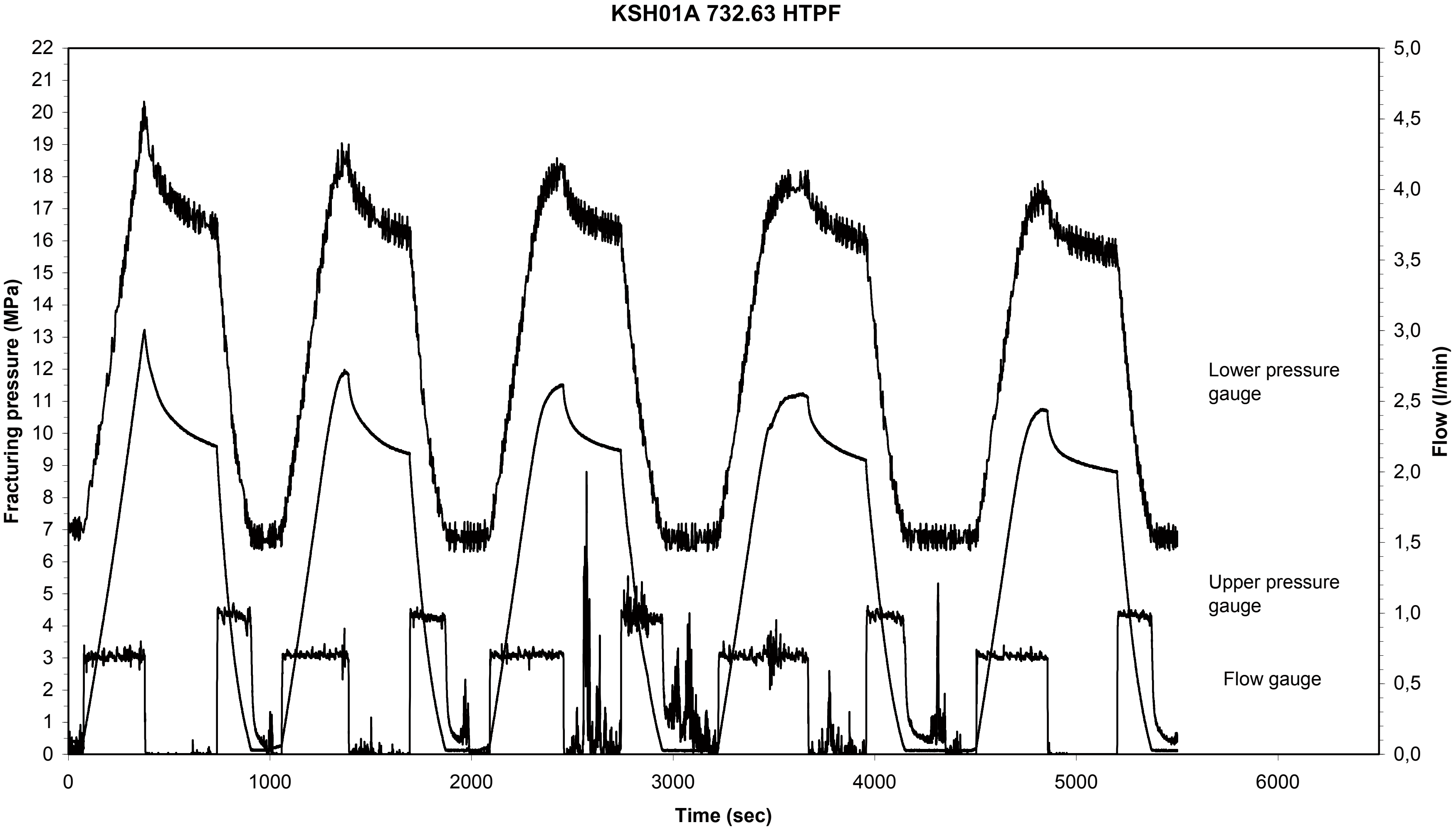


Figure B66. *Pressure and flow record during HTPF tests at 732.63 m borehole length.*

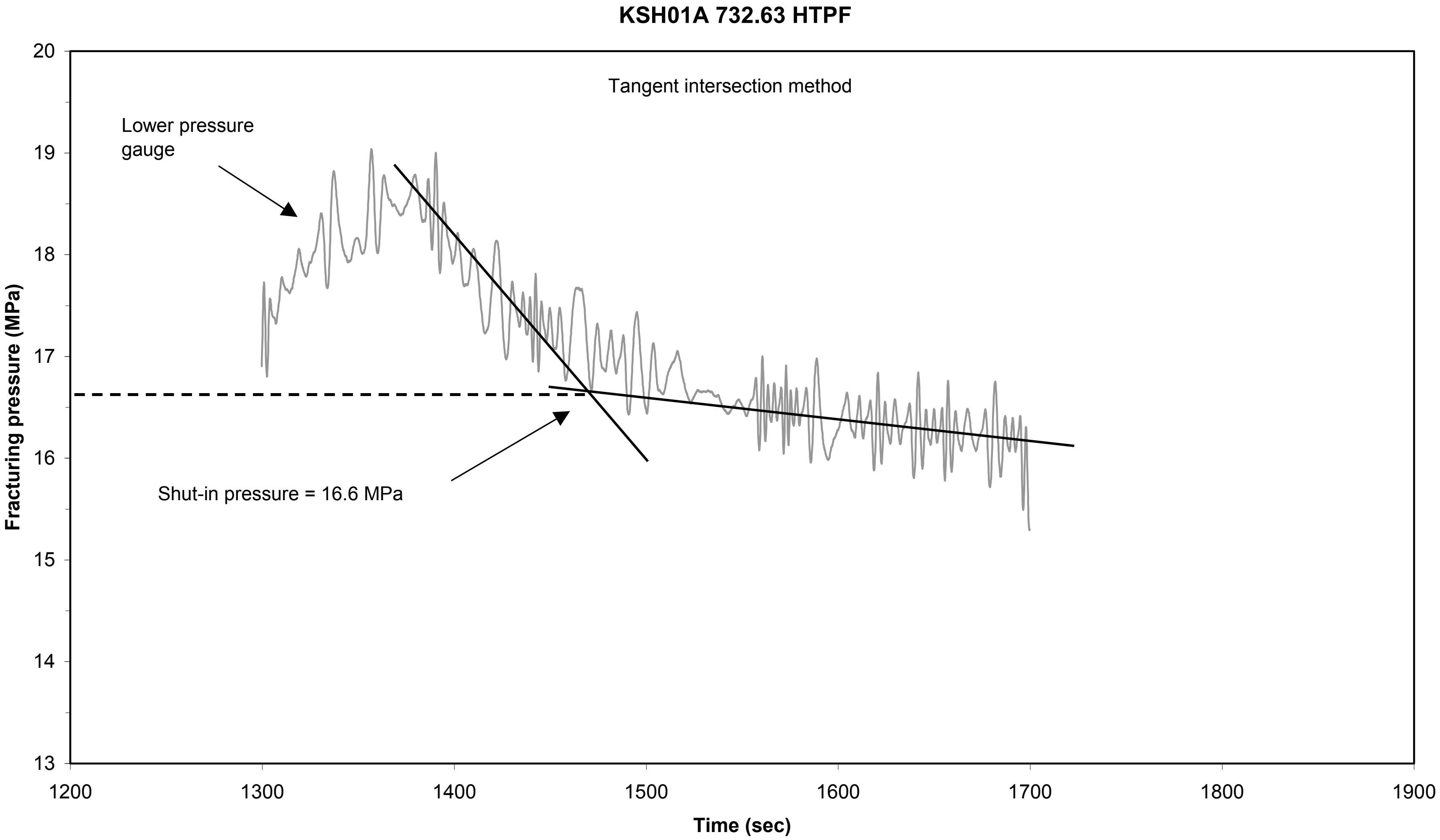


Figure B67. Shut-in pressure determined with tangent intersection method from HTPF at 732.63 m borehole length.

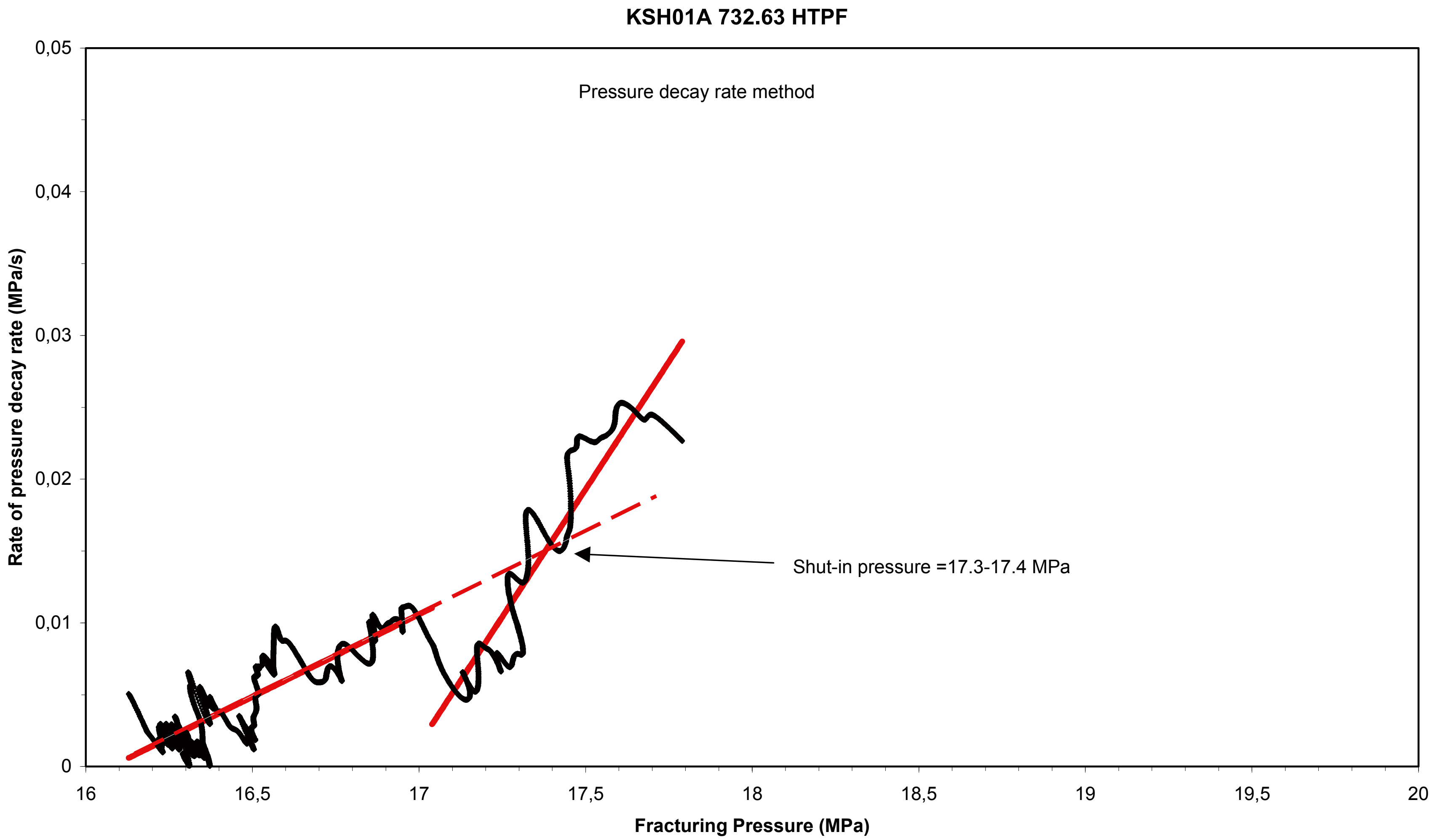


Figure B68. *Shut-in pressure determined by the decay rate method from HTPF at 732.63 m borehole length.*

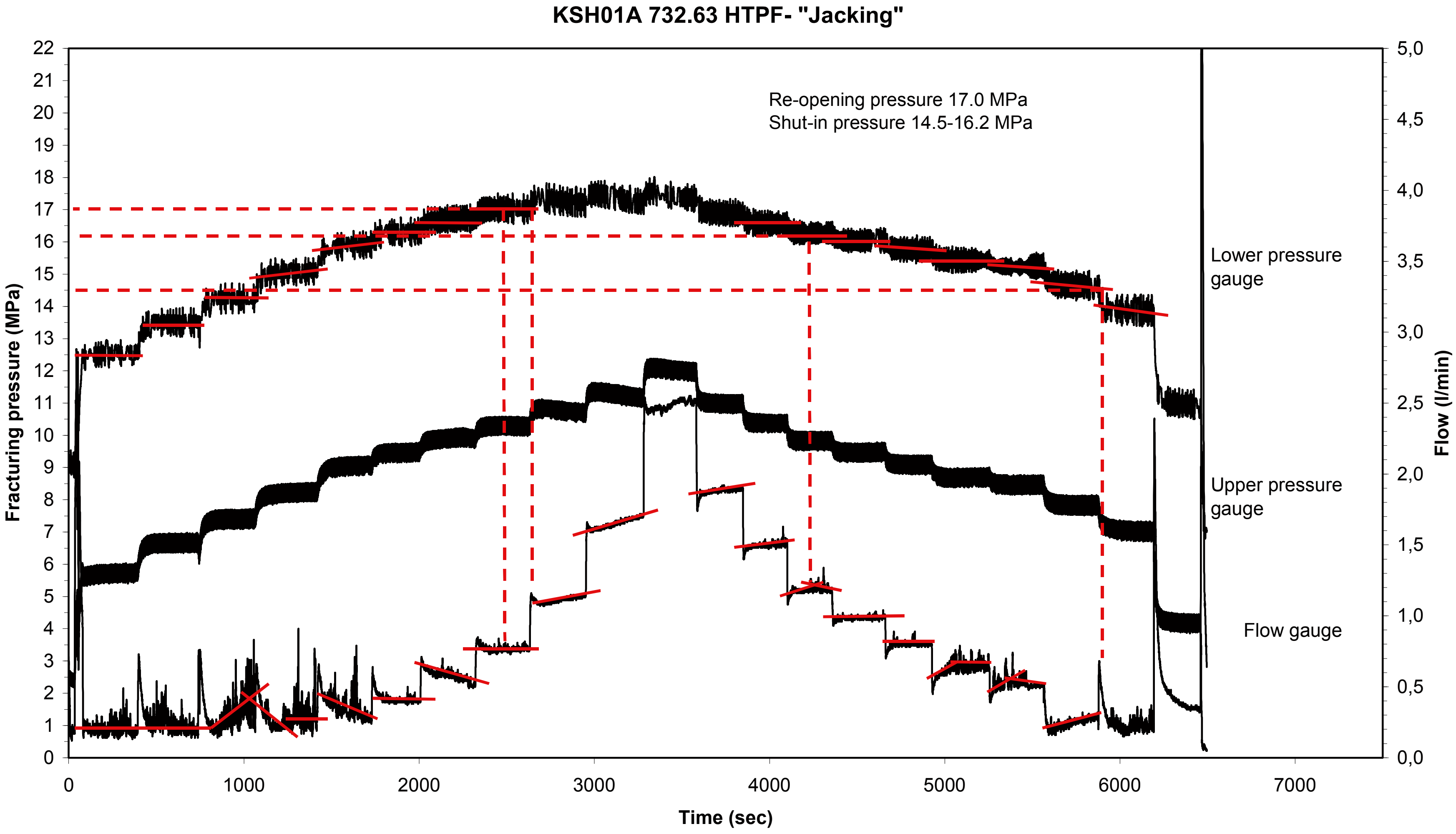


Figure B69. Shut-in pressure determined from jacking test (HTPF) at 732.63 m borehole length.

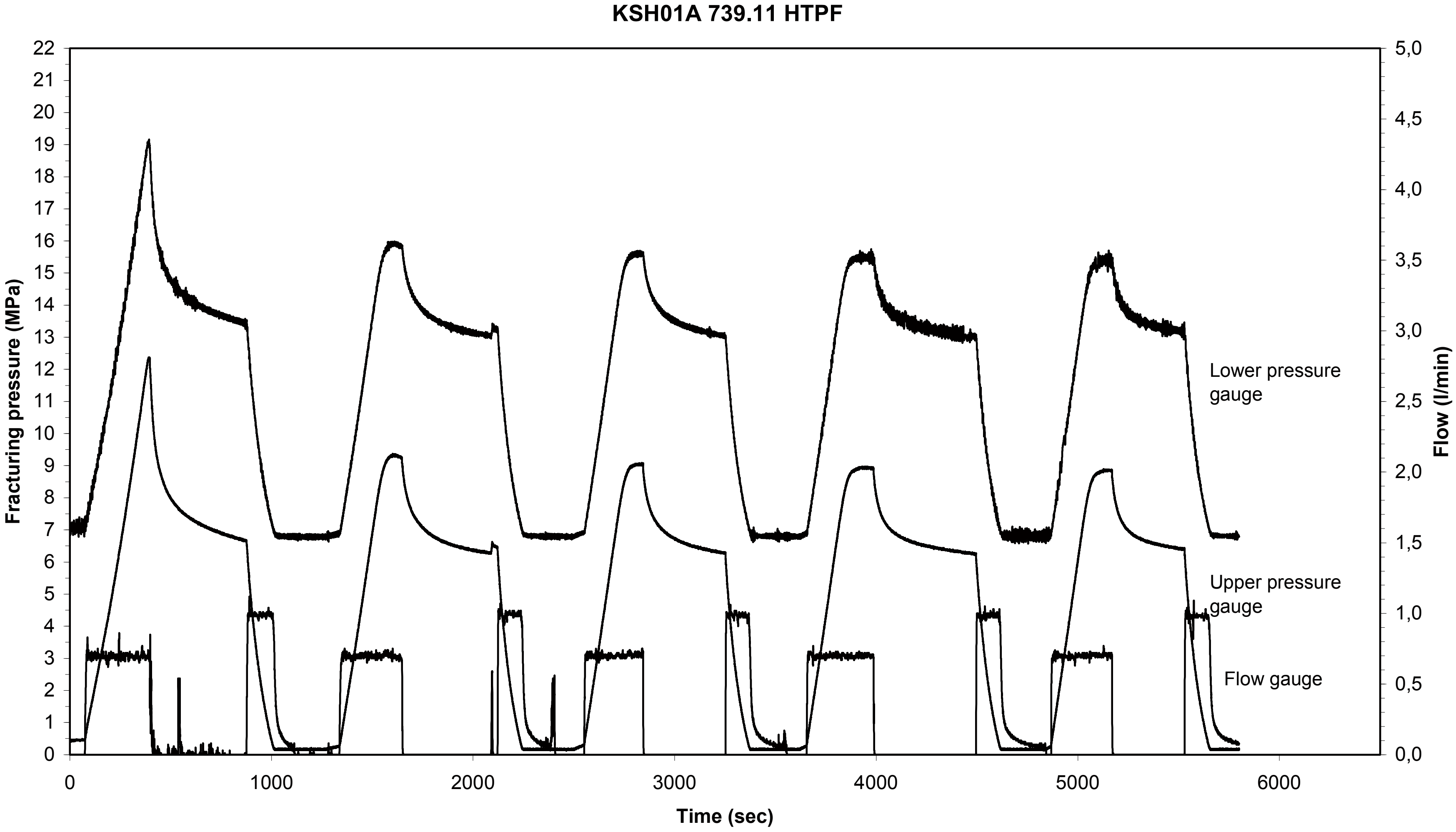


__Figure B70.__ Pressure and flow record during HTPF tests at 739.11 m borehole length.

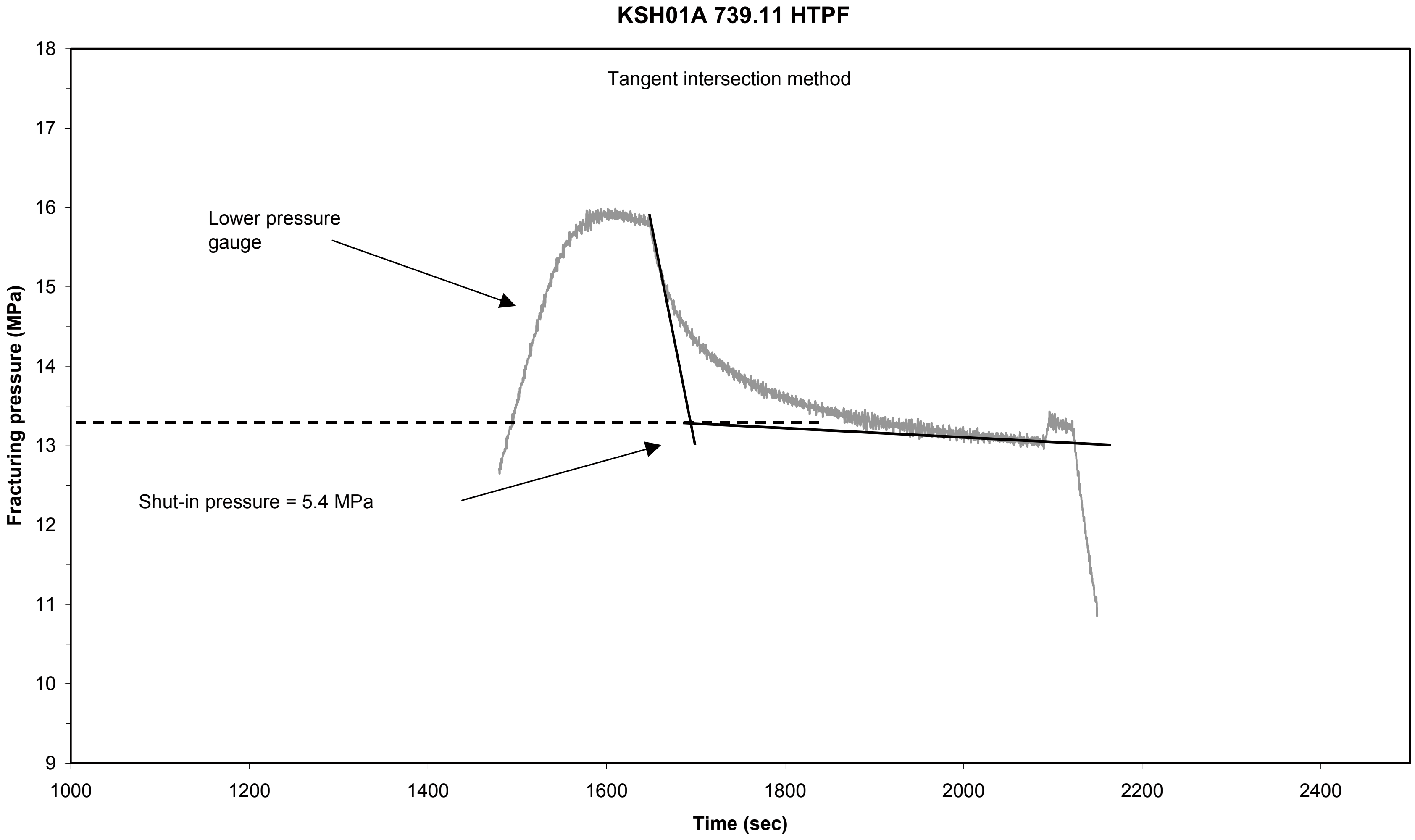


Figure B71. *Shut-in pressure determined with tangent intersection method from HTPF at 739.11 m borehole length.*

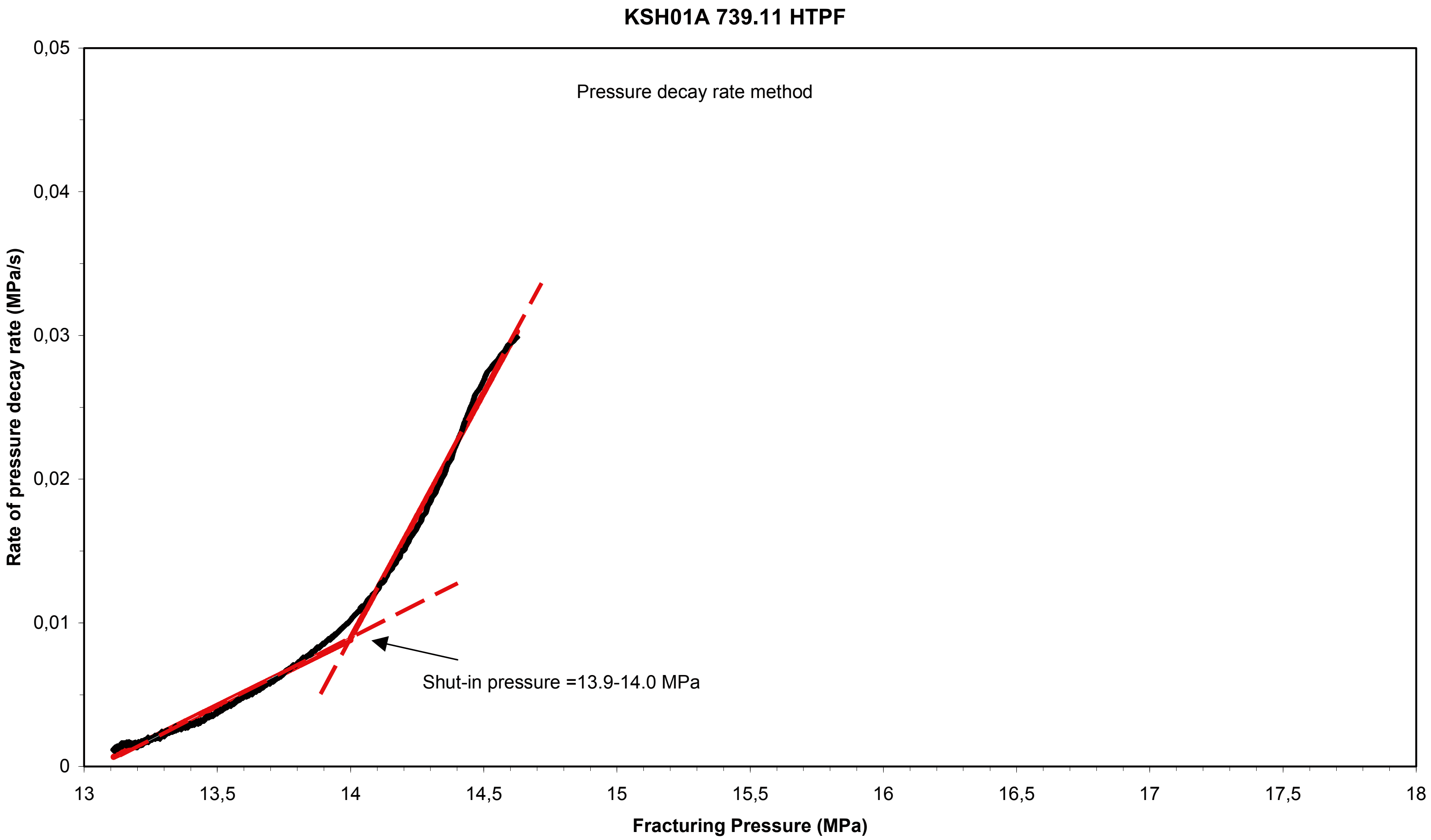


Figure B72. *Shut-in pressure determined by the decay rate method from HTPF at 739.11 m borehole length.*

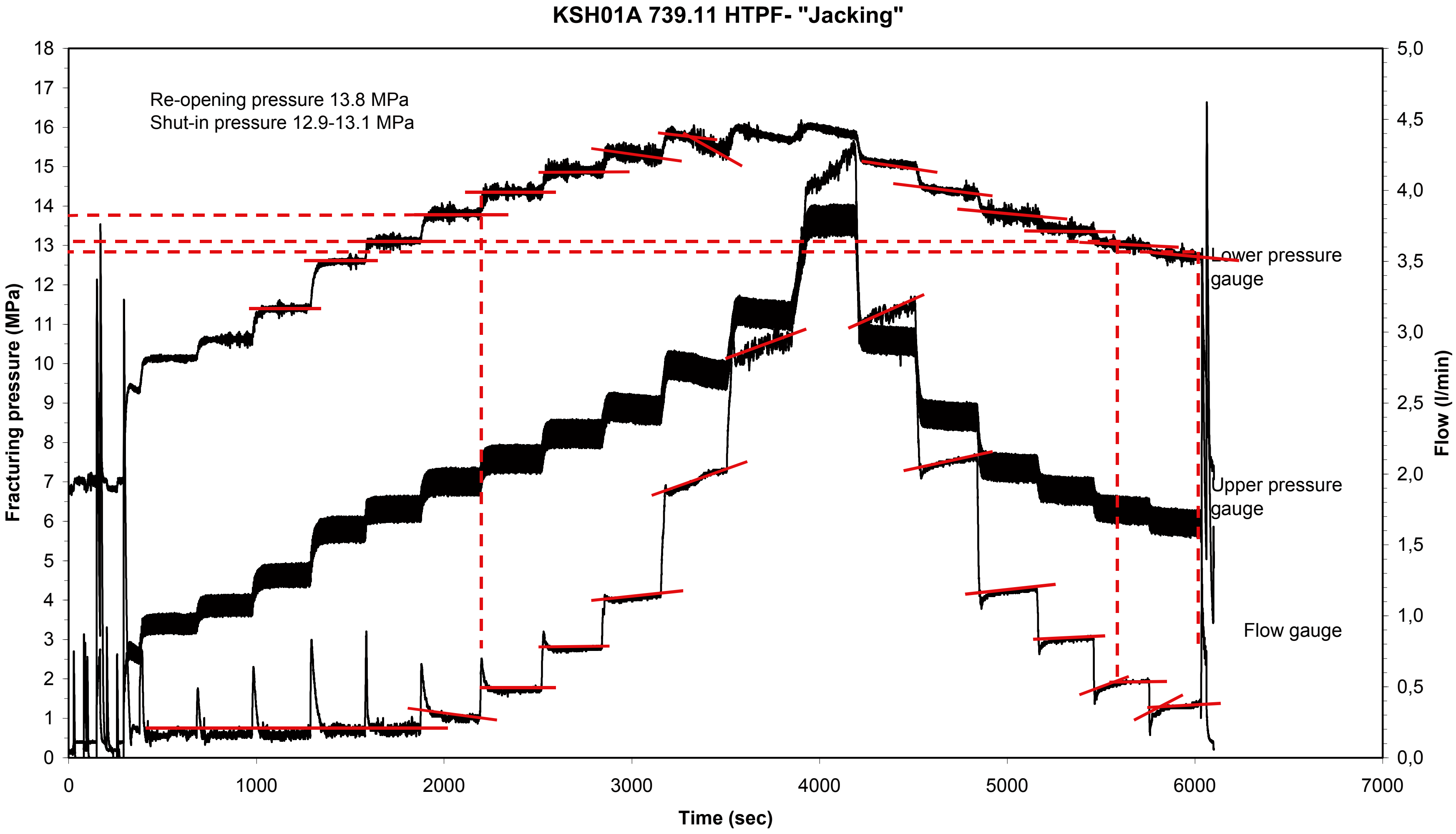


Figure B73. *Shut-in pressure determined from jacking test (HTPF) at 739.11 m borehole length.*

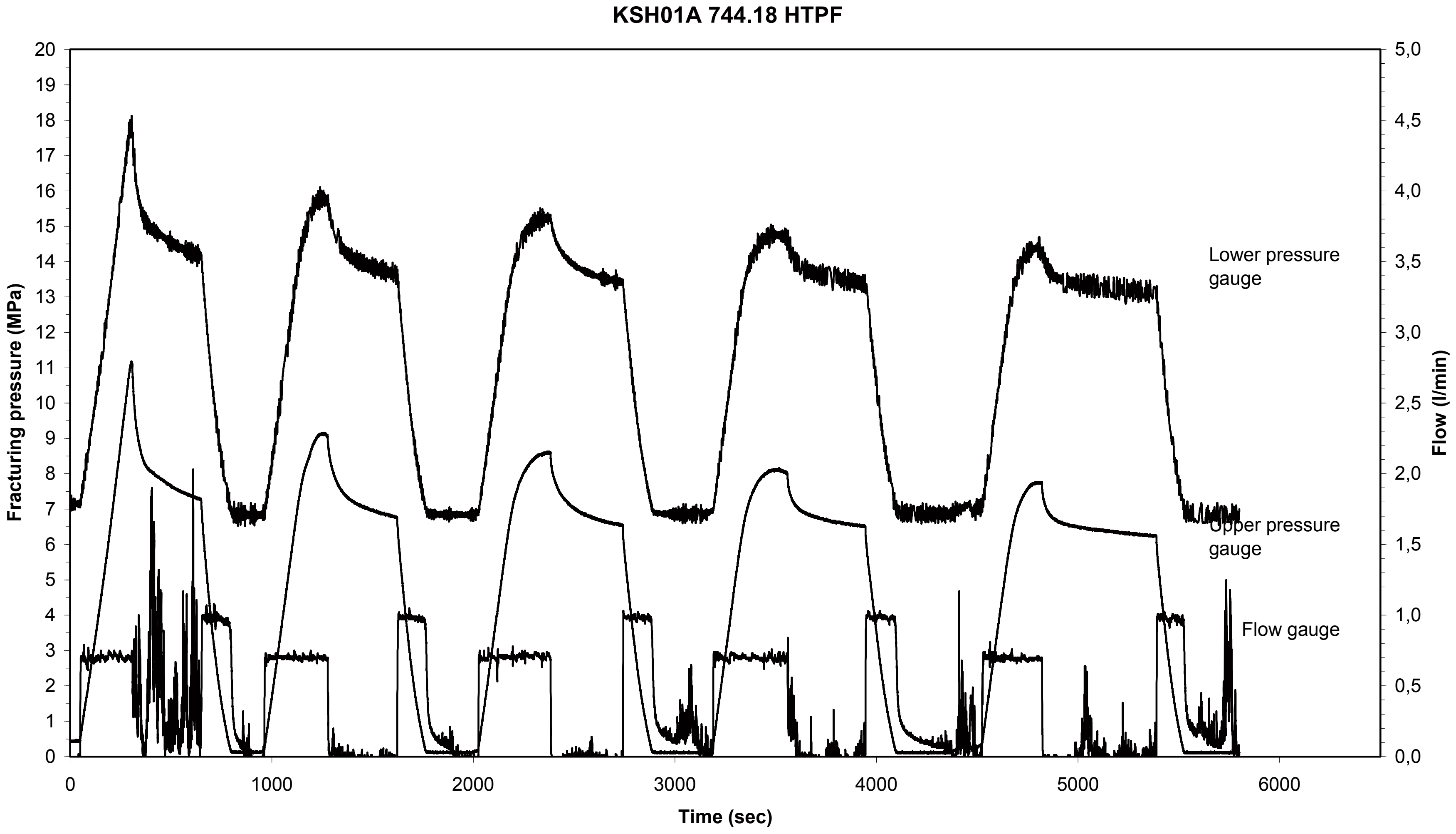


Figure B74. *Pressure and flow record during HTPF tests at 744.18 m borehole length.*

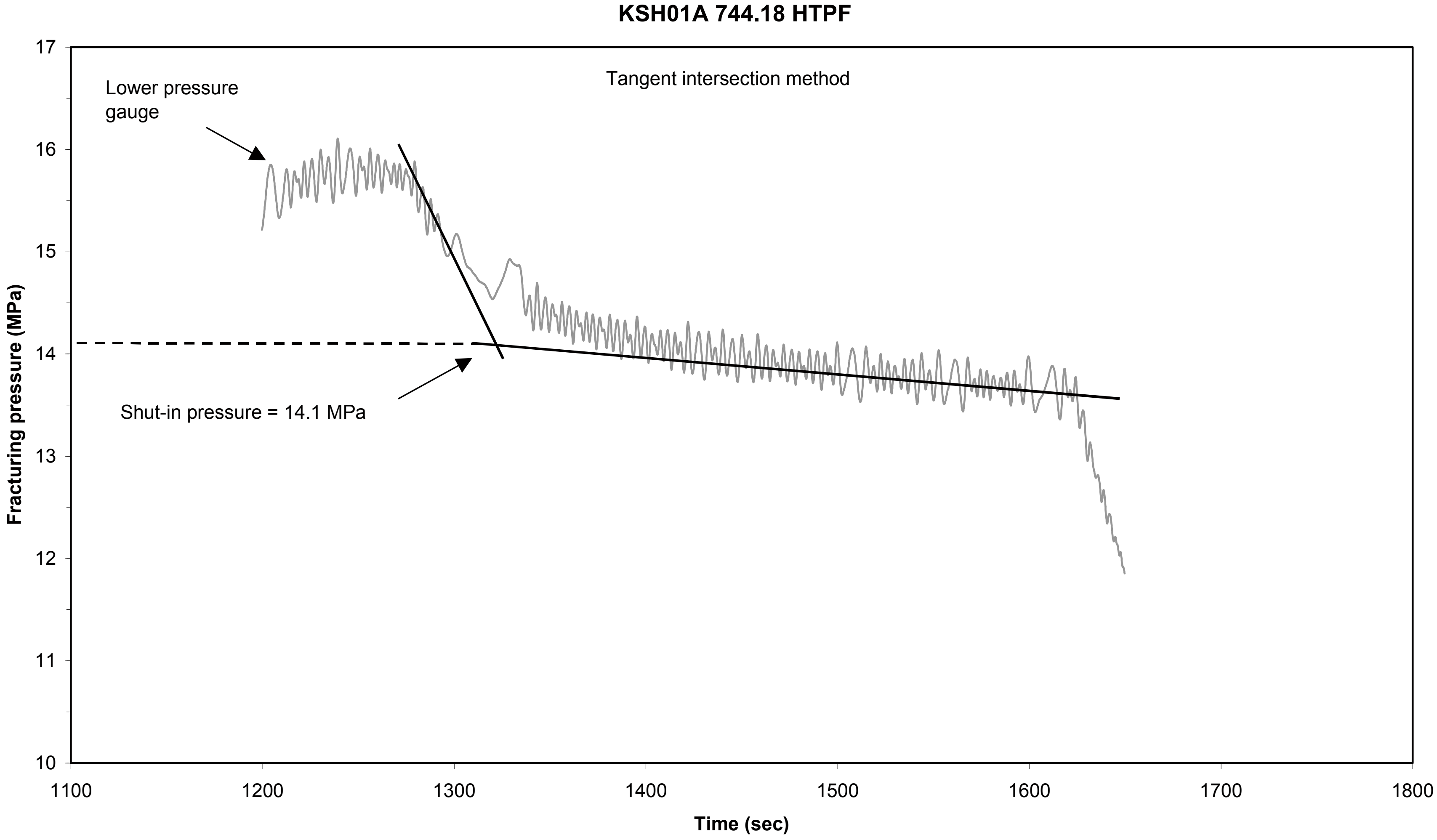


***Figure B75.** Shut-in pressure determined with tangent intersection method from HTPF at 744.18 m borehole length.*

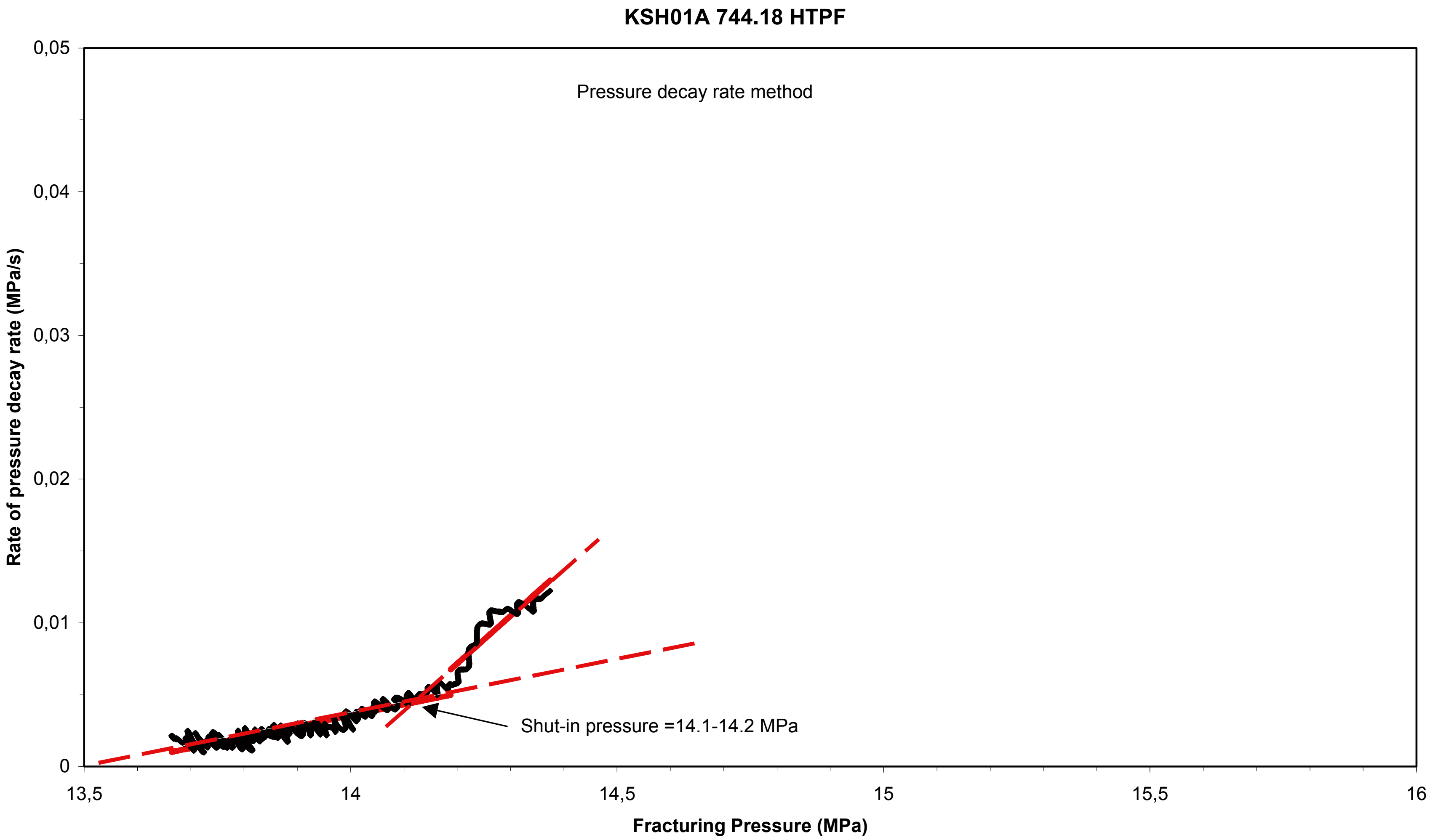


Figure B76. *Shut-in pressure determined by the decay rate method from HTPF at 744.18 m borehole length.*

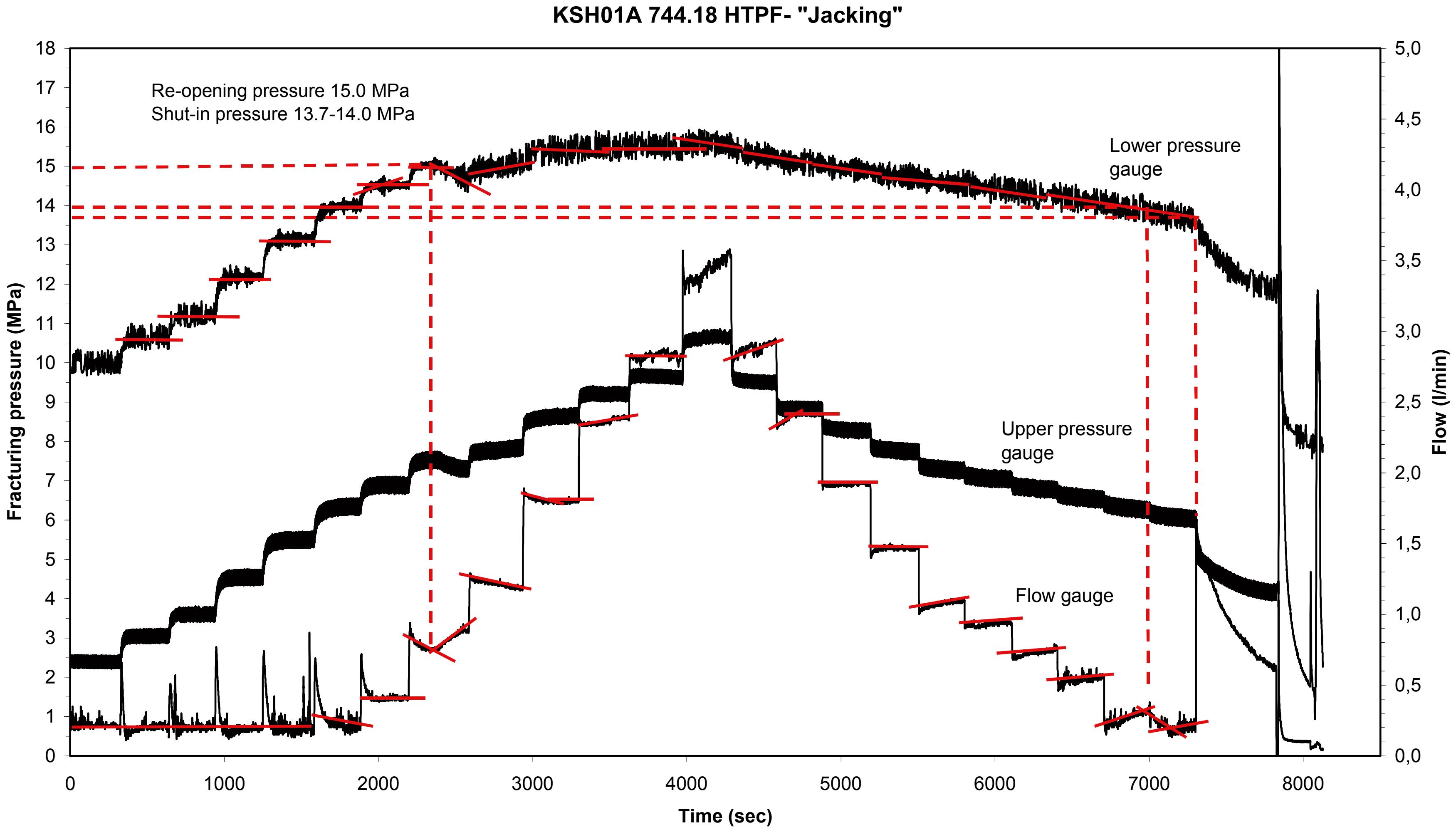


Figure B77. *Shut-in pressure determined from jacking test (HTPF) at 744.18 m borehole length.*

Appendix C

Imprint test data

Table C1. Results from imprints tests after hydro fracturing tests. Bearing of maximum and minimum horizontal stresses determined from imprint tests after HF tests in borehole KSH01A.

Test name	Hole length [m]	Vertical depth [m] **)	Bearing σ_H [°]	Bearing σ_h [°]
KSH01A 179.06 HF	179.06	172.96	111	21
KSH01A 179.90 HF	179.90	173.77	116	26
KSH01A 510.10 HF	510.10	492.72	136	46
KSH01A 529.85 HF	529.85	511.80	119	29
KSH01A 530.75 HF	530.75	512.67	133	43
KSH01A 707.55 HF	707.55	683.44	117	27

Appendix D

Tensile strength data

Table D1. Determined tensile strength at rock cores from borehole KSHSH01A. T_{lab} determined from rock cores from borehole KSH01A.

Test name	Hole length [m]*)	Vertical depth [m] **)	T_{lab} [MPa]	Comments
Tensile strength 179.06 HF	179.50	173.38	17.1	Vertical fracture
Tensile strength 510.10 HF	510.35	492.95	6.96	Sub-horizontal fracture
Tensile strength 529.85 HF	529.85	511.80		Broken at arrival to laboratory
Tensile strength 530.75 HF	531.10	512.99	13.7	Sub-vertical fracture
Tensile strength 707.55 HF	697.88	674.08	11.3	Sub-horizontal fracture

*) Actual position along the borehole where the core was taken.

**) Vertical depth using 75° inclination angle for the borehole.

Five core samples were selected for determination of the tensile strength in laboratory, see Section 5.2.4 and Table D1.

Due to missing core pieces, a sample for tensile tests were not always possible to achieve from the exact location for the hydraulic fracturing tests. Therefore have samples been picked from nearby positions along the borehole with similar geology. The actual position along the borehole for each sample is also shown in the table above and Table 5-4 in the text, at the column “Positions for cores”.

Appendix E

Comparison between different *c*-factors

Comparison of using different *c*-factor for determining $\sigma_{H(I)}$ i.e. maximum horizontal stress with the first breakdown method is shown below. The result is also compared with the maximum horizontal stress determined with second breakdown method i.e. $\sigma_{H(II)}$. Using a *c*-factor between 0.5–0.7 gives from 50% to 90% higher maximum horizontal stress determined with the first breakdown method compared to maximum horizontal stress determine with second breakdown method, see the following tables.

Table E1. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.7 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	11.97	15.8	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529.85		4.872	35.0	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	9.59	28.3	20.5

Table E2. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.6 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	10.26	14.1	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529.85		4.176	34.3	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	8.22	26.9	20.5

Table E3. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.5 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	8.55	12.4	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529.85		3.48	33.6	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	6.85	25.6	20.5

To achieve a maximum horizontal stress determined with the first breakdown method that is in the same magnitude as maximum horizontal stress determine with second breakdown method, the *c*-factor has to be between 0.2–0.3, see following tables.

Table E4. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.4 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	6.84	10.6	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529,85		2.784	32.9	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	5.48	24.2	20.5

Table E5. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.3 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	5.13	8.9	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529,85		2.088	32.2	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	4.11	22.8	20.5

Table E6. Determined $\sigma_{H(I)}$ using T_{lab} with *c*-factor = 0.2 in comparison with $\sigma_{H(II)}$.

Hole length (position for HF tests) [m]	Position for cores (along the hole length) [m]	T_{lab} [MPa]	T_{app} [MPa]	$\sigma_{H(I)}$ [MPa]	$\sigma_{H(II)}$ [MPa]
179.06	179.50	17.1	3.42	7.2	8.2
510.10	510.35	6.9	0	5.7	9.4
529.85	529,85		1.392	31.5	34.6
530.75	531.10	13.7	0	16.8	19.8
707.55	697.88	11.3	2.74	21.4	20.5