Steady-State Permeability Analysis in Unconventional Plays*

Pat Lasswell[1]

Search and Discovery Article #80404 (2014)
Posted September 22, 2014

*Adapted from extended abstract prepared in conjunction with presentation at CSPG/CSEG/CWLS GeoConvention 2013, (Integration: Geoscience engineering Partnership) Calgary TELUS Convention Centre & ERCB Core Research Centre, Calgary, AB, Canada, 6-12 May 2013, AAPG/CSPG©2014

[1]Weatherford Laboratories, Houston, USA (pat.lasswell@weatherfordlabs.com)

Abstract

Shale/tight rock permeability determinations have been a focus of discussion and trial for over 20 years. Crushed pressure decay, pressure pulse, steady state and transient pulse decay methods have been put forward as alternative investigative tools. Each method has attempted to quantify matrix permeability in these unconventional plays.

Rigorous comparative shale/tight rock permeability studies between the main analytical processes have not been documented. But, when limited studies have been conducted, results have not been uniform. As a result, the ability to quantify flow in tight rocks is often discounted.

Steady state permeability is put forward as a valued and defensible method for determining matrix flow in tight plays. Practical steady state analytical procedures designed to investigate both tight gas and tight oil plays will be outlined. Fracture assessment and fracture mitigation will also be discussed as fractures, if present, will otherwise dominate flow.

Introduction

Kamath (1992) investigated the determination of matrix and fracture permeabilities in sandstone using a pressure transient process. Ning (1993) expanded this effort to include naturally fractured Devonian shale. These analytical methods, while elegant and robust, are not commonly employed within the industry.

Instead, a crushed permeability method was “adopted”. This crushed method, developed and presented by Luffel (1993), was one of three methods his team explored. The results from the three methods were compared and the crushed permeability results supported permeabilities determined on the intact shale material. In addition, Luffel considered the positives as well as the negatives associated with this crushed permeability methodology.

However, the crushed permeability process has not resulted in uniform permeability results as supplied by service companies and other investigators. This issue has been cited as being the most serious drawback of the crushed permeability method as it is being conducted at present. In addition, comparative analytical method studies conducted to date have not yet provided a clear answer as to where truth may lie. See Sinha (2011), Sondergeld (2010) and Bustin (2008) among others.

Standards have been put forward as one possible tool for this assessment and that is a reasonable goal. From a practical standpoint, we have pursued a parallel approach. The use of steady-state permeabilities as a benchmark for crushed permeability determinations using available rock samples. In essence, this is a parallel to Luffel's original approach. But as stated, this is viable only if fractures are not controlling the steady-state permeability response.

Steady State Permeability Determinations

Why consider using steady state permeability as a benchmark for permeability determination in shale and tight rock plays? In review:

1. Steady state gas permeabilities have long been recognized as a standard for quantifying Darcy flow in conventional as well as tight gas sand plays. Its' use in shale/tight rock analysis has also been put forward by multiple investigators.
2. Parallel in-situ reservoir mechanisms aside (diffusion, Knudsen flow), flow characterization can be accomplished well into the nano-Darcy range.
3. Tests can be relatively straight forward and the results repeatable.
4. Horizontal samples are preferably taken from conventional whole core as either 1" or 1.5" diameter sized plugs.
5. Intact matrix and bedding structure can be reasonably preserved and studied.
6. Confining stress effects can be investigated.
7. Varied fluids/gases can be used in the determinations. Backpressure can be employed.
8. Multi-point Klinkenberg gas permeability studies can be performed.
9. Matrix fractures, both representative and recovery artifacts, should be removed from the system as these will dominate the flow.
10. Long test times are consistently forwarded as reasons not to consider this method. However, running multiple samples in parallel effectively removes this concern.

Steady State Gas Permeability Determinations

Steady state permeability determination in shales/tight rocks should involve more than a conventional API RP40 approach. A monitored permeability test is recommended so that equilibrium flow can be more effectively documented. This is a reasonable alternative, as flow in these rocks is often volumetrically limited. The tests are typically conducted on preserved rock fabric or on cleaned and dried rock fabric.

As-received state is the standard sample state for these permeability analyses when gas plays are investigated. The sample is mounted at net confining stress and a constant N_2 gas pressure is applied to the inlet core face. The gas drive pressure typically ranges from 30 psi to 150 psi. Outlet flow is monitored vs time using a bubble tube ranging from 0.1 cc to 1 cc total volume depending upon a sample's permeability. A monitored steady-state gas permeability test at a single drive pressure requires several hours to several days to complete. As stated, this test is an effective tool from a time perspective when multiple test cells are employed. The graph below (Figure 1) is representative.

As investigations have shifted from gas plays to oil plays, much of the industry has moved from using as-received state material and instead focused on using clean and dried material for gas permeability determinations.

API RP40 indicates that steady-state drive pressures should be kept low for low permeability rocks. (This finding was based on unsteady state permeability studies done over 10 years ago.) Using a pressure at or below 1 psi is not practical for this type of analysis. In fact, conventional permeability equipment developed by Frank Jones uses a maximum pressure of 60 psi for rock less than 1 mD. Since gas permeability is dependent upon the pressure used in the determination, the drive pressure needs to be documented along with the permeability value. With the statement about the maximum gas drive pressure in mind, it is important to consider whether permeability remains linear over the range of pressures used in investigating these tight rocks.

The following graph (Figure 2) illustrates the point that use of higher gas drive pressure is defensible by looking at the permeability pattern of a given sample. (Permeabilities do vary significantly in magnitude, but the linear response is representative.) This test was conducted at net confining stress on a dry state sample using N_2 at drive pressures ranging from 4 psi to 150 psi. Note that in the graph, the 60 psi pressure point mentioned as being used in conventional analysis, is indicated by an open symbol. The data clearly shows that using permeability drive pressures higher than 1 psi is supported.

Steady-State and Crushed Gas Permeability Patterns

Investigators have stated that few repeatable data patterns exist between permeabilities determined using intact reference methods and permeabilities determined using crushed permeability methods.

If fractures are either not present, or are sealed, it has been our experience that reasonable data patterns should be the norm. This finding supports the conclusion stated by Luffel (1993). (The question of sample fractures is one of the main issues surrounding the use of steady state permeability as a defensible analytical tool. It is important to note that most of these fractures are not visible unless magnification above 100x is used. The problem is not trivial. This topic will be addressed in the final section.)

The graph below (Figure 3) is comprised of data condensed from four separate North American shale/mudstone play projects. For each intact plug sample, conventional properties were conducted following Dean-Stark extraction and vacuum drying. The plugs were inspected for fractures and fractures were either not present or were epoxy filled. The plugs were then crushed to yield particles less than 1/8” in diameter, re-extracted, re-dried and properties re-determined. The pattern is indicative of most unconventional plays we have investigated to date: the plug based porosities are often suppressed and steady-state permeabilities fall within a ½ order of magnitude of the crushed permeabilities. The steady-state permeabilities are typically higher.

Such method comparisons are best conducted on a unique set of plugs with each plug subjected to the sequential analysis steps. A reasonable alternative is to take twin plugs, side by side in the same bedding planes, one for each analysis method.

In summary, permeability standards may not be widely used by the industry, but steady-state gas permeabilities can be used as a benchmark for crushed gas permeabilities if the steady-state tests are conducted using a defensible protocol.

As Received Steady-State Effective Oil Permeabilities

With the shift from shale gas plays to shale oil plays the last few years, methods developed for gas plays were adapted and modified so that viable core analysis information could be obtained for oil plays.

One such adaptation was the development of steady-state effective oil permeabilities from gas based steady-state permeability determinations. This process can be summarized in the following steps:

1. Assess the intact as-received plug samples for fractures. It is highly recommended that if fractures are present, that they be sealed with epoxy so that a matrix flow is determined.
2. Saturate the samples with light mineral (decalin) to displace most of the residual gas saturation.
3. Mount each sample at a designated net confining stress.
4. Flush each sample with the light mineral oil using a constant pressure drive of approximately 500 psi. Monitor effluent clarification and production stability over multiple weeks until a reasonable flow equilibrium is demonstrated. Typical time needed is from 6 to 8 weeks.
5. Throughput volumes are usually very low due to sample and time constraints.
6. Flow response is subject to the effects of possible asphaltene precipitation.
7. Multiple sample tests can be conducted in parallel.

The following graph (Figure 4) presents data from three typical samples taken from two separate shale plays. The material was analyzed in an as-received state and no fractures (visible under magnification of 500x) were identified either before or after testing.

While the Koswi test as outlined is presented as a routine test, it can also be done at temperature or with back pressure. Other options include: extended flow times, fluid substitutions, and varied net confining stress regimes. This test does not presume to answer the question of whether an interval will be productive or economical. Perhaps it is best used as a comparative tool or as an indicator. Additional support by petrographic, geochemical, and pore throat data is highly recommended.

The following graph (Figure 5) provides a comparison of steady-state effective oil permeability and crushed gas permeability data. The analyses were sequentially conducted on the same samples and no fractures were identified in the plugs. Please note that not all data sets are this straightforward with respect to data patterns.

Equipment Set-up for Steady-State Effective Oil Permeability Determinations

This photograph (Figure 6) shows a typical set-up for conducting steady state oil permeabilities. Included are hydrostatic test cells with a common constant drive manifold. Tests are conducted in parallel using 1 cc pipettes to monitor down-steam flow volumes.

Fracture Assessment in Conventional Gas Permeability Determinations

The prevalence of matrix fractures in shales led the GRI investigators (Luffel 1993) to develop a crushed permeability alternative to traditional steady-state permeability determinations. Twenty years later, conventional analysis is being requested for unconventional plays and the same fracture issue remains. But, this is not as simple as identifying obvious fractures and bed partings. In fact, it has been observed that in many shale/mudstone plays, the plugs that have been subjected to conventional property analysis are fractured with up to 60% to 80% of the plugs affected. It is of note that often these fractures are not identified unless magnification (+100x) is employed. The existence of these fractures dominates the permeability response and the reported permeabilities can be several orders of magnitude to high when steady state or pressure decay processes are used. It would be straight forward if the fractures were representative of in-situ reservoir conditions but since this is usually not the case, the presence of fractures needs to be addressed. This issue equally applies to both gas and oil plays.

The following graph (Figure 7) illustrates the issue of fractures in conventional permeability determinations when conducted on a shale interval. If intact plugs are analyzed, the steady state and crushed permeabilities should agree within a half order of magnitude. Clearly the example does not fit that expected pattern. This is the typical situation. Examination of the plugs under magnification indicated that all but one sample exhibited axial fractures. The individual data points are color coded denoting the length of the observed fractures.

The photographs below (Figure 8) illustrate that observed fractures typically run axially along the plug length. The fractures roughly follow the bedding planes.

Dealing with Fractures in Plugs

Fracture documentation is an important step in understanding conventional permeability response in unconventional plays. How to address flow dominated by fractures is another question. Since separation of induced fracture flow from “legitimate” fracture flow is difficult at best, one solution is to remove the fracture flow component and to concentrate on just the matrix itself. The process advocated here, employs the injection of epoxy into the fractures that are present and then determining steady-state permeability on the resulting “intact” matrix. The key is to effectively fill the fractures without injecting epoxy into the available pore structure. An added benefit in the method is that all rock types can be investigated, not just those that remain intact.

The question of whether fractures are completely filled by epoxy injection is a common one. This is hard to answer directly or quantitatively on each sample tested. Certainly permeability data patterns can be compared before and after epoxy treatment, but this might be somewhat subjective. Instead, examination of the plug faces under 500x magnification is recommended along with documentation via photography. The existence of poorly sealed fractures has been rarely observed using this method. If a fracture is not sealed properly, the epoxy treatment can be repeated on a given sample.

During initial method trials, the following test sequence was successfully employed to investigate the viability of the epoxy injection process. Its' success is probably the best confirmation of the epoxy injection method.

1. Determine steady state permeability on an intact sample.
2. Generate an open axial fracture.
3. Fill the fracture with epoxy and repeat the permeability measurement.

The next three photographs (Figure 9) document the epoxy injection process. The plugs shown below (mudstone left, shale right) were epoxy treated to fill existing fractures.

The above photographs (Figure 9) show epoxy injected into existing fractures without entry into the surrounding pore structure. Left: a tight gas sand example. Right: a shale sample. Epoxy injection pressure is "matched" to the pore structure: 20 psi was used on the tight gas sand sample and 1000 psi was used on the shale sample.

With respect to the use of epoxy, an additional point needs to be addressed. If a sample is treated with epoxy, it will no longer react to net confining stress as it would have in an intact un-treated state. Currently, there is no way around this point. Comparably, the permeability offset due to un-treated fractures is of much greater magnitude than the permeability offset related to the stress behavior shift associated with the use of epoxy.

In Summary

Steady state permeability has long been a tool used in assessing flow in conventional and unconventional plays. It is absolutely applicable to shale/tight rocks plays as long as appropriate time and consideration is given to the analytical process. In particular, as a minimum, fractures should be assessed and described. Consideration should be given to the filling of fractures with epoxy so that a matrix only response can be measured.

References Cited

American Petroleum Institute, 1998, Recommended Practices for Core Analysis, RP40.

Bustin, R.M., A.M.M. Bustin, X. Cui, D.J.K. Ross, and V.S. Murthy Pathi, 2008, Impact of Shale Properties on Pore Structure and Storage Characteristics: SPE 119892.

Kamath, J., R.E. Boyer, and F.M. Nakagawa, 1992, Characterization of Core Scale Heterogeneities Using Laboratory Pressure Transients: SPE 20575, p. 219-227.

Luffel, D.L., C.W. Hopkins, and P.D. Schettler, 1993, Matrix Permeability Measurement of Gas Productive Shales: SPE 26633, p. 261-269.

Ning, X., J. Fan, S.A. Holditch, and W.J. Lee, 1993, The Measurement of Matrix and Fracture Properties in Naturally Fractured Cores: SPE 25898, p. 555-569.

Sinha, S., E.M. Braun, Q.R. Passey, S.A. Leonardi, A.C. Wood, T. Zirkle, J.A. Boros, and R.A. Kudva, 2012, Advances in Measurement Standards and Flow Properties Measurements for Tight Rocks Such as Shales: SPE 152257.

Sondergeld, C.H., K.E. Newsham, J.T. Comisky, M.C. Rice, and C.S. Rai, 2010, Petrophysical Considerations in Evaluating and Producing Shale Gas Resources: SPE 131768.

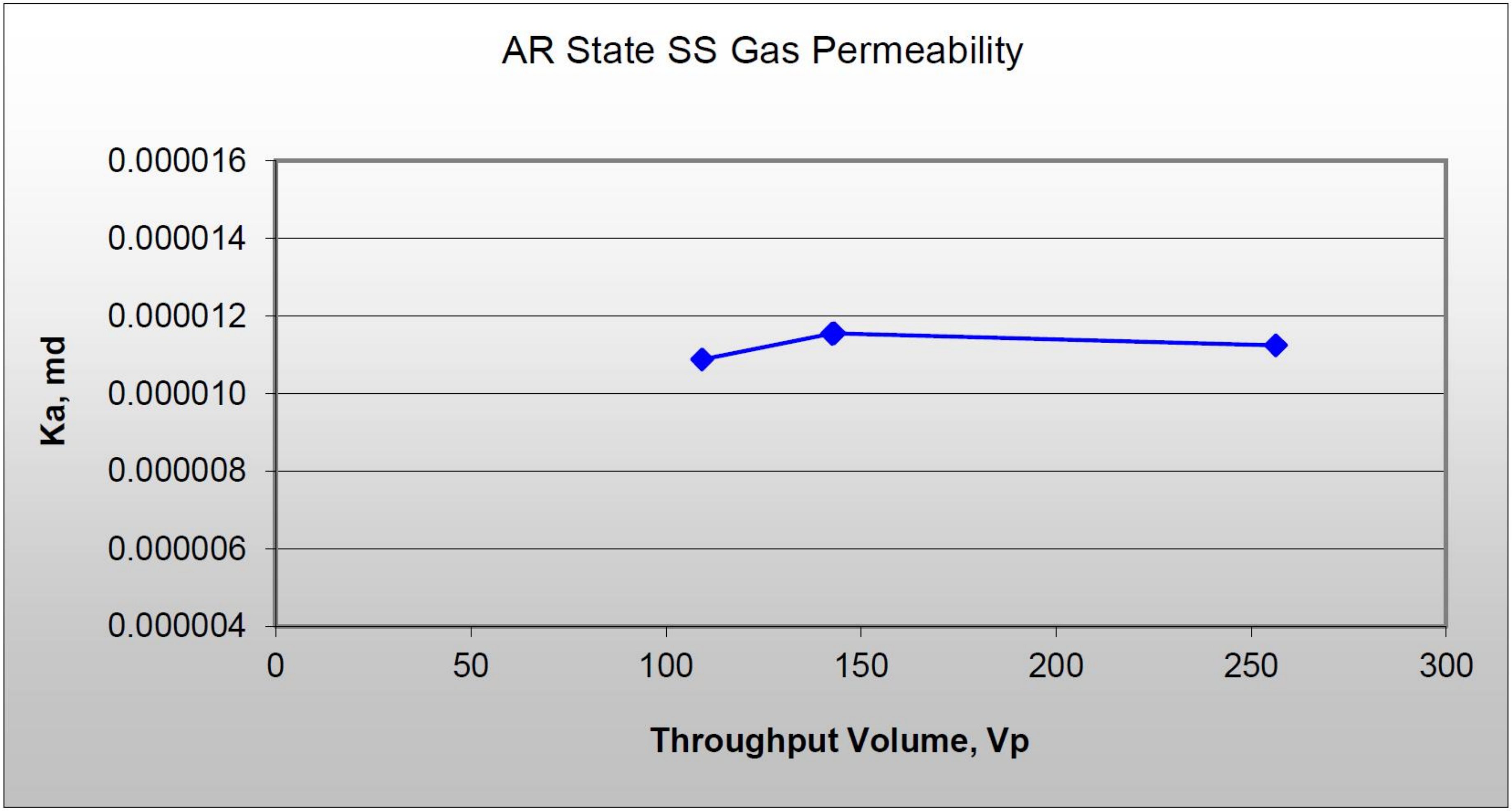

Figure 1. Monitored Steady State Gas Permeability Determination.

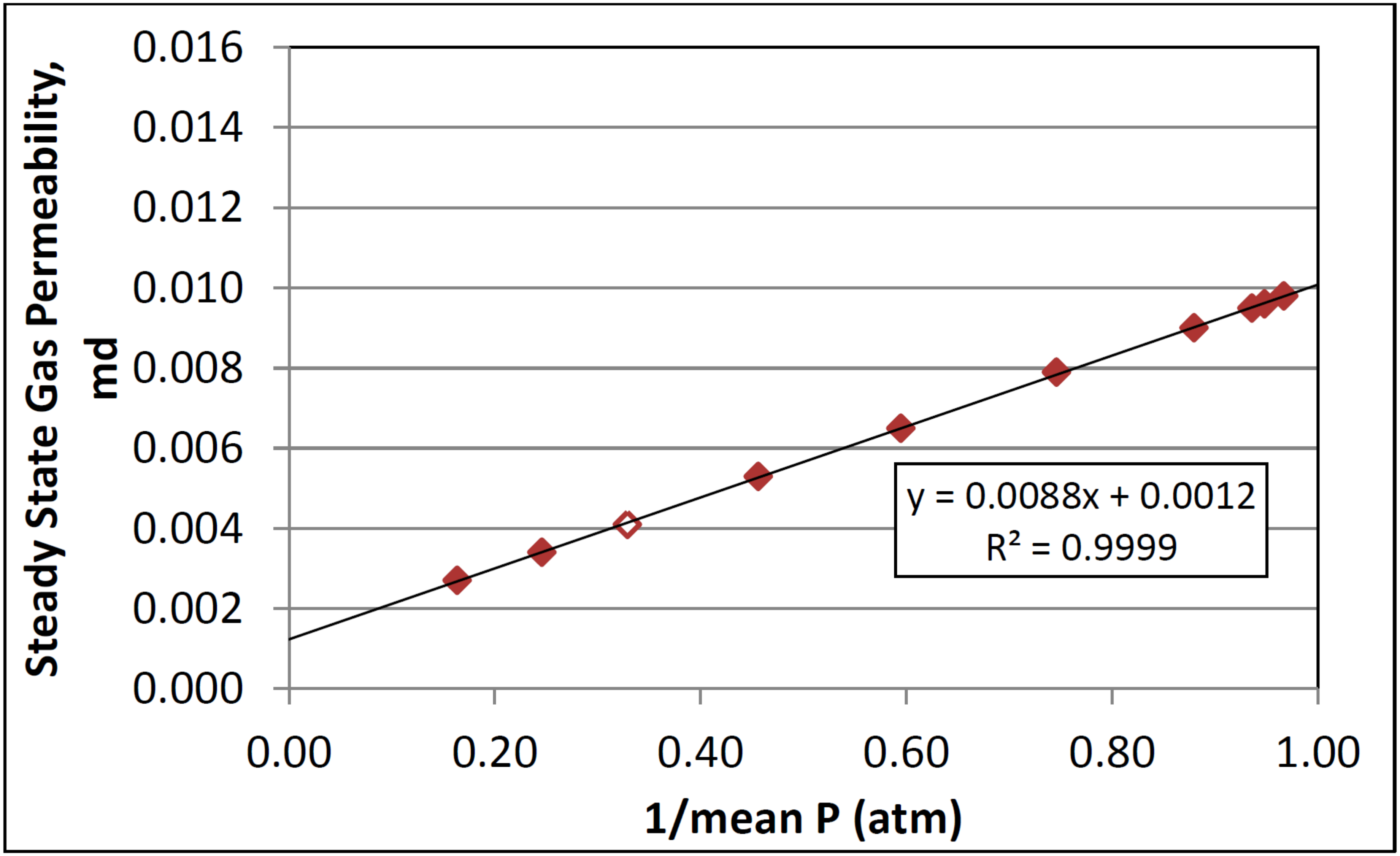

Figure 2. Multi-Point Steady State Klinkenberg Gas Permeability Determination.

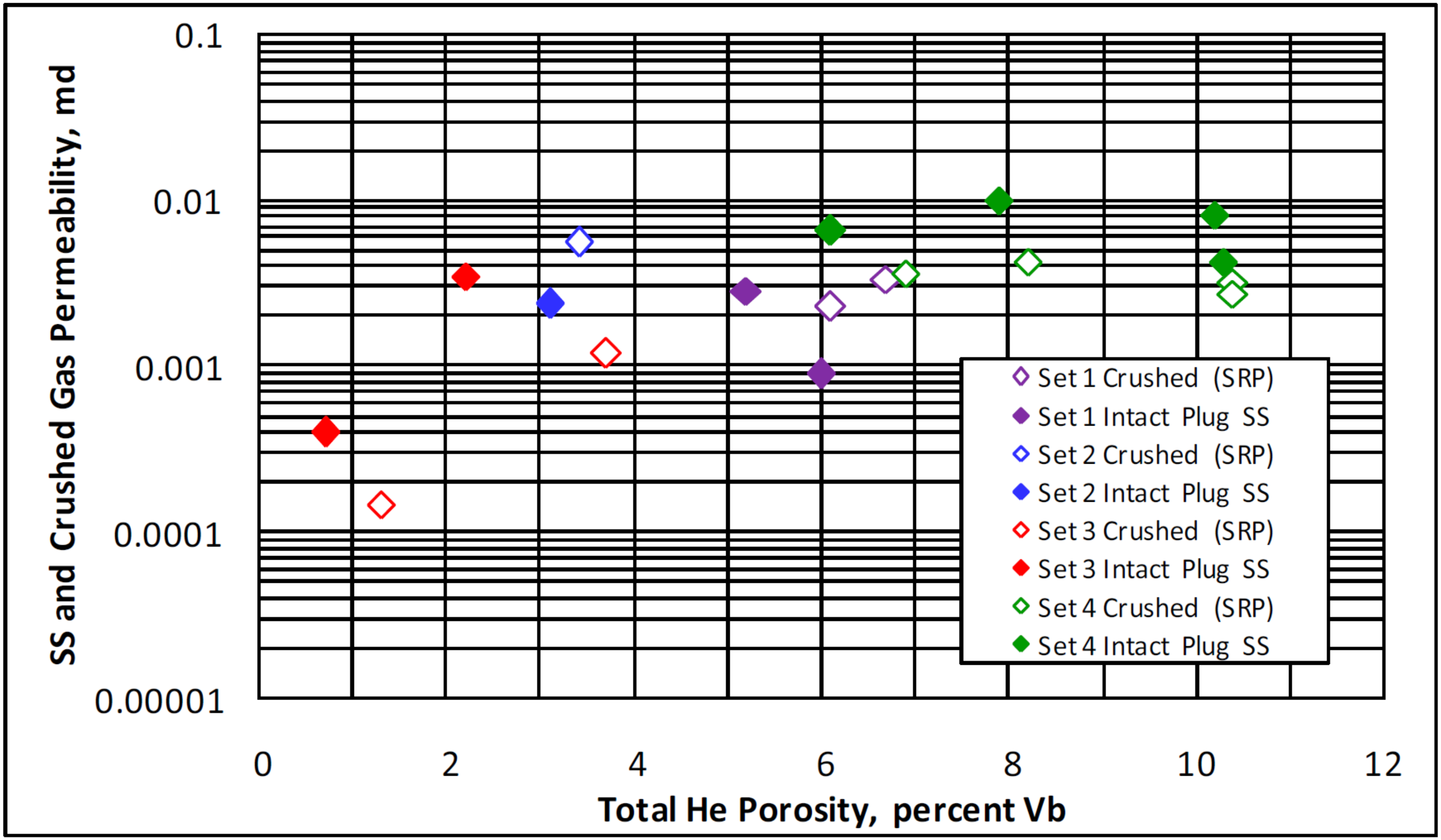

Figure 3. Steady State vs Crushed Gas Permeability Data Pattern.

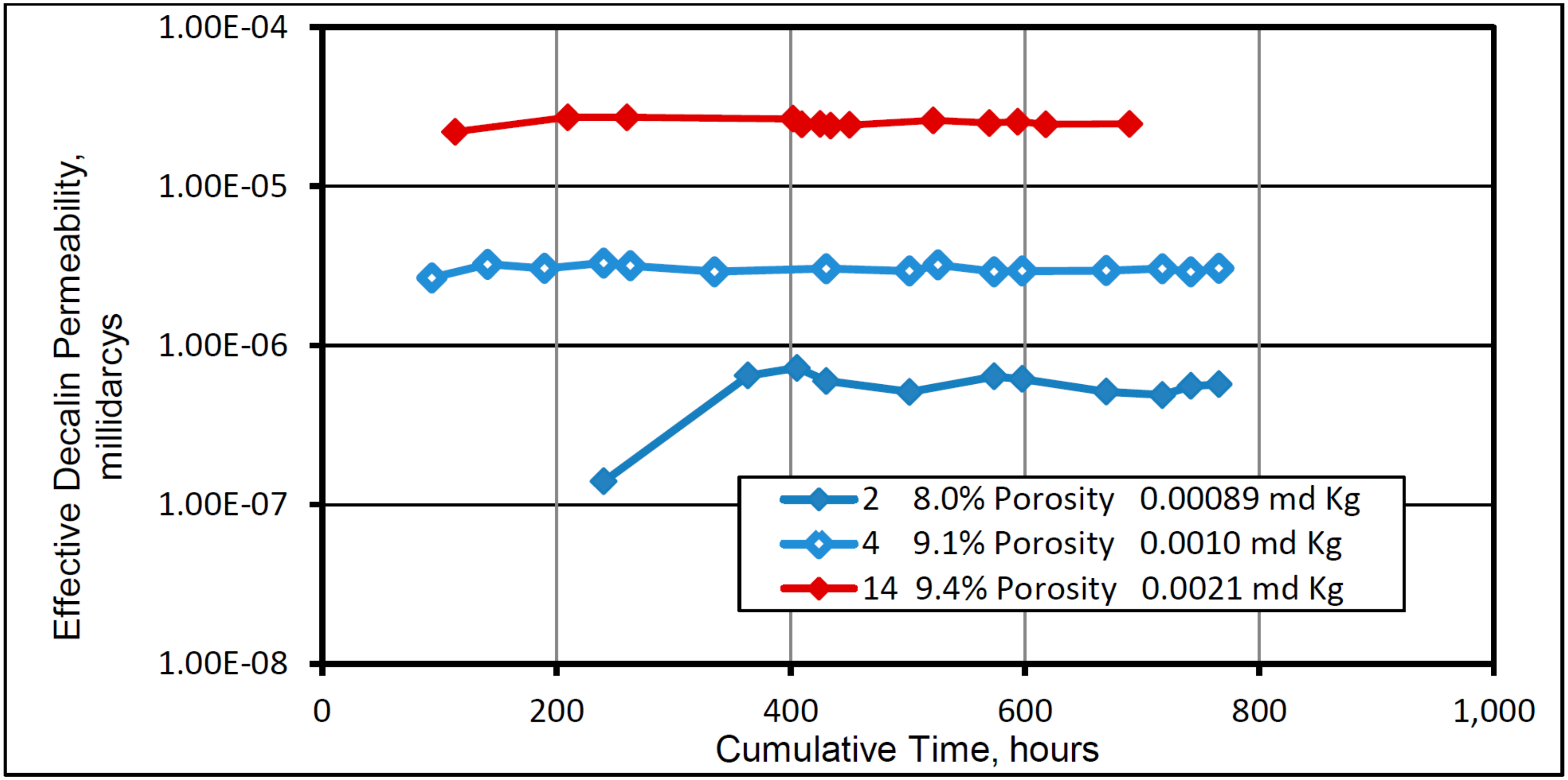

Figure 4. Monitored Steady State Effective Oil Permeability Data at Swi.

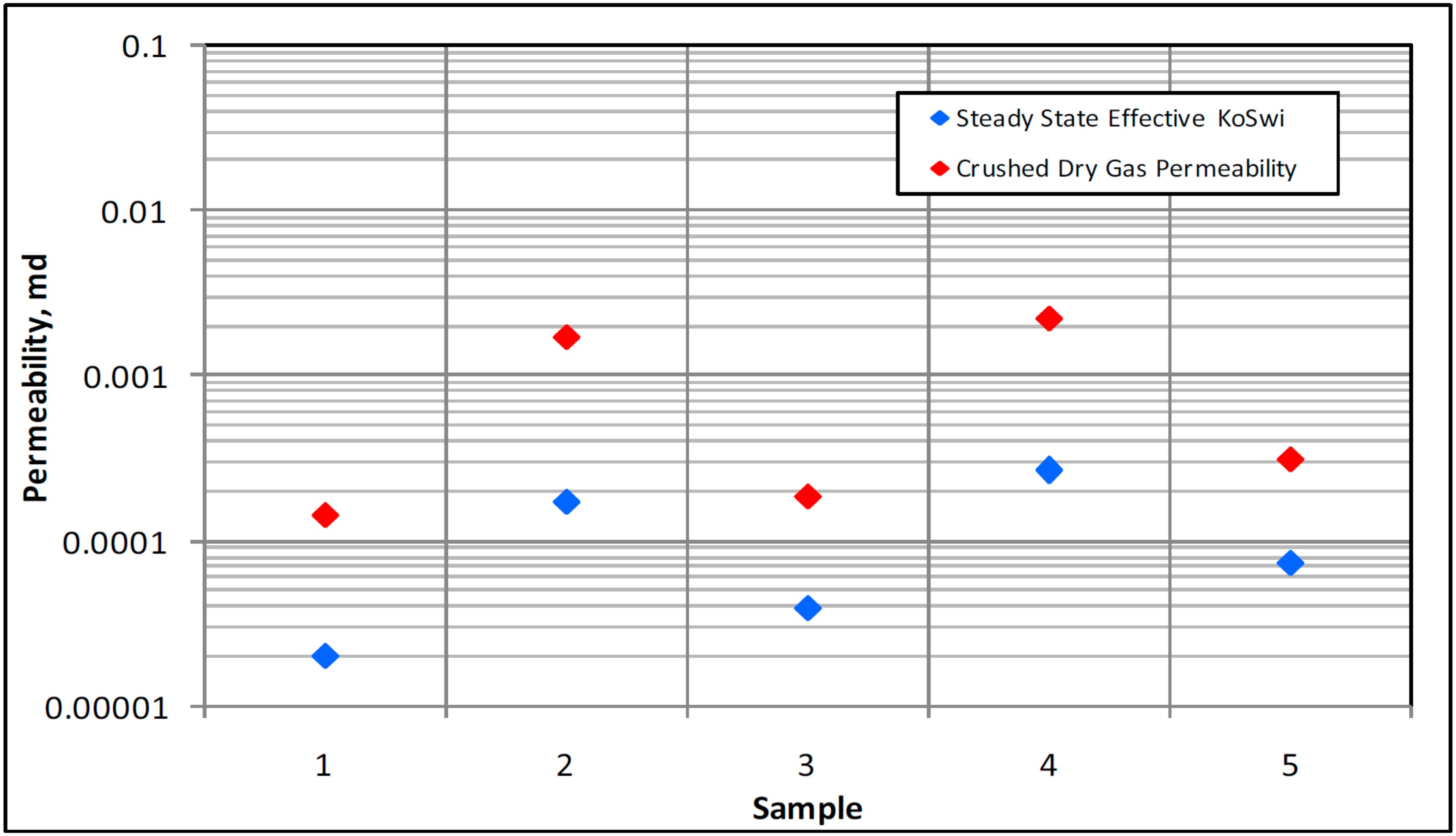

Figure 5. Effective Steady State Oil Permeability vs Crushed Gas Permeability Data Pattern.

Figure 6. Hydrostatic Test Cells.

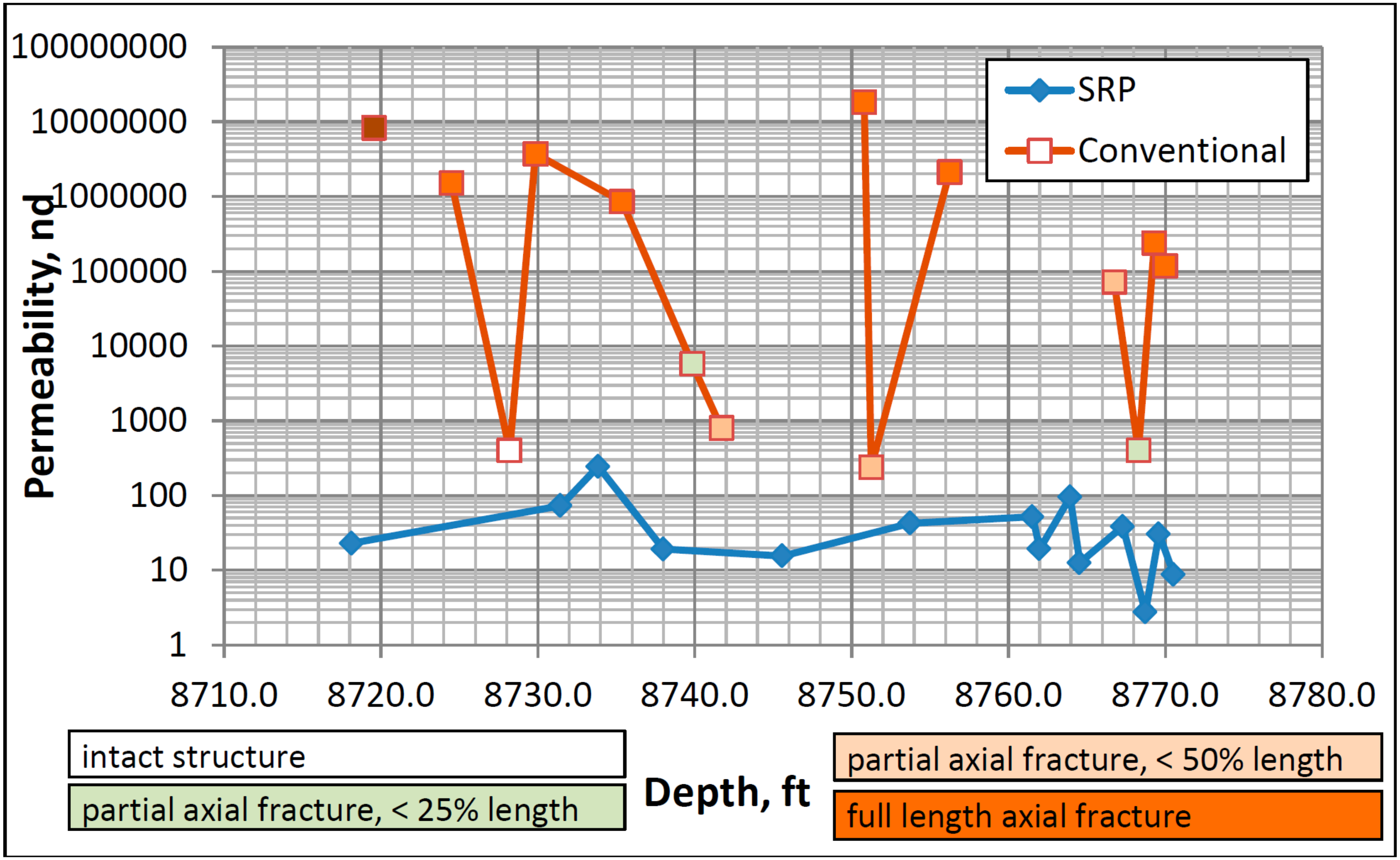

Figure 7. Crushed Permeability and Steady State Permeability Data Patterns.

Figure 8. Horizontal Plug Fractures Recorded Using Approximately 200x Magnification.

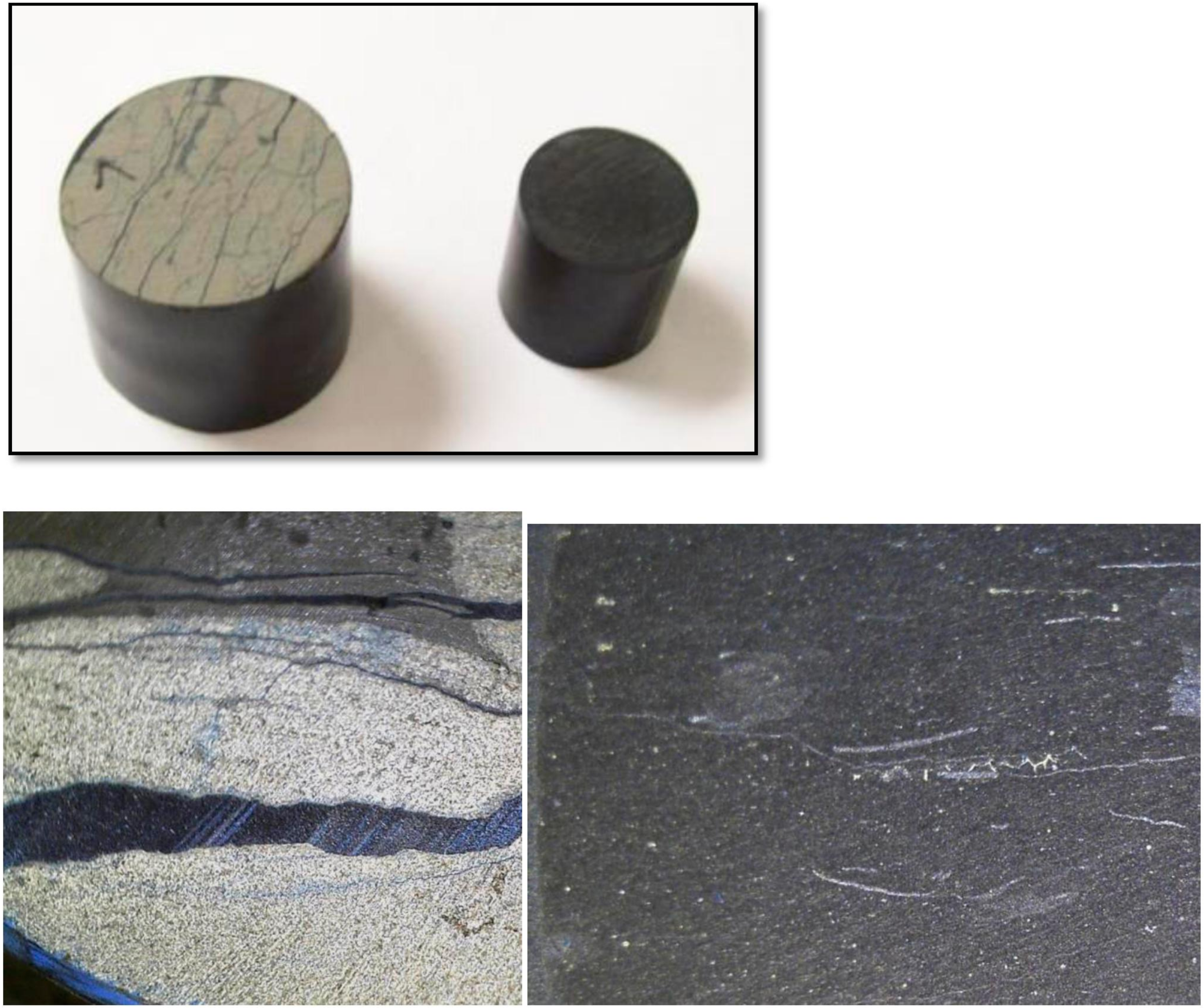

Figure 9. Documentation of the epoxy injection process.