

Does Fracture Conductivity Recover After Unloading?

Yana Fradkin and Dawid Hanak

Abstract. Returning a fracture to its initial effective stress need not return it to its initial conductivity. This note separates conductivity retention under load from recovery after unloading and proposes two complementary hysteresis metrics. A synthetic cycle demonstrates that a large rebound from the most compressed state can coexist with substantial permanent loss. The framework is intended to improve cyclic-test reporting and to prevent an unloading curve from being interpreted as evidence that the original fracture geometry has been restored.

What does recovery mean?

A loading cycle contains at least three states: an initial condition, a maximum-load condition, and a return to the initial stress. Contact mechanics allows permanent deformation during such a cycle [1], while coupled joint models link deformation to hydraulic response [2]. Comparing only the second and third states answers whether conductivity increased after unloading. It does not answer whether the first state was recovered.

Define C_o as initial conductivity, C_m as conductivity at maximum stress, and C_r as conductivity after returning to the initial stress. All three must be measured using the same phase, temperature, and flow convention. Otherwise a fluid change can mimic mechanical recovery. Existing shale-water damage experiments provide a direct reason to control that history [3].

Kakkar's thesis summary states that the original conductivity was not recovered when stress returned from 5,000 to 1,000 psi in either propped or unpropped specimens [4]. The 2017 study includes cyclic loading among its experimental variables [5]. The related 2019 report describes an 80% unpropped-conductivity decrease after one cycle between 300 and 4,000 psi [6]. These observations should retain their test-specific context and should not be merged into one cycle with a common stress range.

In propped fractures, embedment and pack changes offer possible irreversible mechanisms [7, 8]. For unpropped surfaces, asperity yielding and changing contacts are the relevant mechanical candidates. A non-local closure model provides a framework for interacting asperities [9]. The similarity of a conductivity curve alone cannot establish which mechanism dominated.

Worked example: four views of one loading cycle

Proposed cyclic metrics using synthetic $C_0 = 1.00$, $C_m = 0.10$, and $C_r = 0.30$ mD-ft.

Retention at peak load.

$$C_m / C_0 = 0.10 / 1.00 = 10\%.$$

Return-state recovery.

$$C_r / C_0 = 0.30 / 1.00 = 30\%.$$

Recovered fraction of lost capacity.

$$(C_r - C_m) / (C_0 - C_m) = 0.20 / 0.90 = 22.2\%.$$

Permanent loss at return.

$$1 - C_r / C_0 = 1 - 0.30 / 1.00 = 70\%.$$

Choosing a recovery measure

Rebound, restoration, and the comparison endpoint

In the worked example, unloading increases conductivity from 0.10 to 0.30 mD-ft, a threefold rebound. However, the specimen still retains only 30% of its original capacity. The recovered fraction of the loading loss is $0.20/0.90 = 22.2\%$. Both statements are mathematically correct, but they describe different denominators. Any report of percentage recovery should therefore state the denominator explicitly.

These metrics do not isolate chemistry, creep, or mechanical plasticity. A time-matched control is needed because the return-state measurement occurs later than the initial measurement. One practical design uses neighboring specimens: one follows the full cycle, one remains at the reference stress, and one experiences the same fluid exposure without the high-stress excursion. Differences between these paths can guide attribution, subject to specimen variability.

The return-to-original ratio is suitable when the question is how much of the initial capacity survives the complete cycle. The ratio of returned to peak-load conductivity instead describes rebound from the most compressed state. The fraction of lost capacity recovered measures the part of the loading loss subsequently regained. These metrics need not rank specimens in the same order, because their denominators encode different questions.

Consider two synthetic cycles beginning at 1.0 mD-ft. Specimen A falls to 0.1 and returns to 0.3; specimen B falls to 0.5 and returns to 0.6. A has a threefold rebound, while B has only a 1.2-fold rebound. Yet B retains twice A's return-state conductivity. The recovered fractions of the loading loss are approximately 22.2% for A and 20% for B. Ranking by that last measure would favor A slightly while ranking by final capacity strongly favors B.

Select the primary metric before examining the curves and report the absolute endpoint values alongside it. If two metrics answer relevant questions, keep both rather than combining them into an unexplained score. Near a zero loading loss, the recovered-fraction denominator becomes unstable; a very large ratio may then reflect a small denominator rather than a dramatic physical response. A useful report identifies that condition and avoids giving the ratio more significance than the underlying measurements warrant.

Immediate and delayed response

A recovery measurement needs a time as well as a stress. State how long the specimen remains at the return stress before C_r is measured, and use the same stabilization criterion applied to the initial state. A rapid reading and a delayed reading answer different questions if the system is still evolving. Neither should be silently substituted for an equilibrium value. The proposed comparison therefore treats return stress, elapsed time, temperature, and measurement phase as a single endpoint definition.

A practical protocol can record the full return-state trajectory while also specifying one comparison time in advance. This prevents selection of the most favorable point after seeing the curve. Record instrument drift using a separate reference and record specimen drift using a time-matched control where possible. The two controls address different causes of change.

If conductivity rises after unloading, possible interpretations include reopened flow paths, continuing redistribution of fluid, or changing particle transport. The conductivity record alone does not distinguish them. Exposure-sensitive conductivity experiments justify retaining fluid history [3], while closure models motivate simultaneous mechanical observations [1, 9]. These sources motivate the measurement design; they do not make every observed recovery a purely mechanical effect.

A rapid increase in conductivity immediately after unloading and a slower increase during the return hold should be reported separately if the measurement system can resolve them. Define an early observation time and a later comparison time before analyzing the trajectory. The difference between those readings describes delayed change over the specified interval. It does not establish the mechanism responsible for that change or prove that recovery has reached its final value.

For an illustrative sequence, let conductivity at peak stress be 0.10 mD-ft, immediately after unloading 0.20 mD-ft, and after the prescribed hold 0.30 mD-ft. Relative to an original 1.00 mD-ft baseline, the early and later returned fractions are 20% and 30%. Calling the entire increase from 0.10 to 0.30 instantaneous rebound would misdescribe the observation. Calling the later 30% value complete recovery would misdescribe the baseline comparison.

Interpretation requires awareness of apparatus response. Pressure equilibration and storage in the measurement system can affect how quickly a change is observed. A separate reference experiment can characterize that response without claiming to reproduce the rock's evolution. If the instrument cannot distinguish an immediate jump from a short transient, report the time resolution. This makes the recovery result reproducible and avoids assigning a physical timescale more precisely than the experiment can support.

Designing the loading history

A cycle as a sequence of states

Specify ramp rate, dwell duration, pressure control, and the criterion for hydraulic stabilization at every step. Preserve the rock before testing [10] and characterize the rock-proppant system where applicable [11]. Barnett laboratory measurements illustrate the importance of fracture configuration [12], and shale conductivity procedures address experimental flow control [13]. The proposed protocol adds explicit return-state metrics to those broader measurement concerns.

At minimum, collect aperture or displacement measurements and effluent solids alongside conductivity. Use repeated cycles only after documenting the first, because a conditioned specimen is no longer a virgin surface. If fluid chemistry changes between cycles, classify the result as a combined mechanical-chemical history. Partially propped configurations warrant particular care because placement can change the distribution of contact stresses [14].

A cyclic test is easier to interpret when each transition is named explicitly: initial reference, loading, peak hold, unloading, return hold, and any subsequent exposure or rest period. Attach the actual stress, pressure, temperature, and elapsed time to each state. This prevents a measurement taken during unloading from being compared with one taken after a long return hold as though they represented the same endpoint.

A proposed record should also preserve the reason for each transition. An operator may have ended a hold because a stability criterion was met, because the planned duration expired, or because the instrument approached its operating limit. These events have different implications. If a hold ends before stabilization, retain the trajectory and describe the endpoint as time-specific. Do not infer an equilibrium value by assuming that the unobserved continuation would have become flat.

The state sequence can be represented by a simple event list linked to the raw hydraulic record. Repeated cycles then share a common structure while retaining their different starting conditions. The preserved-shale studies provide motivation for recording irreversible loading and exposure effects [4, 5, 6], but the event structure is a proposed reporting method. Its value is that another

analyst can reconstruct which state was compared with which, including interruptions and deviations from the intended schedule.

Repeated cycles and time-matched controls

Define a cycle-specific recovery $H_j = C_{\text{return},j} / C_{\text{initial},1}$ using the original baseline, and a local recovery $h_j = C_{\text{return},j} / C_{\text{initial},j}$ using the start of each cycle. Both can be useful, but they answer different questions. The first tracks cumulative change. The second describes recovery within the current cycle after earlier damage has already occurred. Their denominators should never be left implicit.

For a synthetic sequence, let the original conductivity be 1.00 mD-ft and the first returned value be 0.30 mD-ft. Suppose a second cycle begins at 0.30 and returns to 0.24 mD-ft. Local second-cycle recovery is 80%, while recovery relative to the original specimen is 24%. Reporting only the 80% value would conceal most of the accumulated loss. These selected numbers extend the arithmetic example and are not observations from the cited studies.

Plot the entire sequence rather than overlaying cycles after renormalizing each one to unity. Keep cycle number and dwell time attached to every point. If the sequence appears to stabilize, additional cycles or a longer hold may test that interpretation, but an apparently repeatable short sequence does not establish indefinite stability. The relevant question is whether the tested history spans the intended use.

The return-state measurement always occurs later than the initial one. A proposed control therefore remains at the reference stress for the same elapsed duration while experiencing a compatible fluid and temperature history. Its purpose is to estimate the change that occurs without the high-stress excursion. Independent specimens are required if the control and cycle cannot be applied without altering the same specimen's history.

Suppose a cycled specimen returns to 0.30 of its initial conductivity, while a time-matched control remains at 0.90. The cycled fraction is one third of the control fraction. This contrast is different from the statement that 30% of the original capacity remains. Both may be informative. The ratio should not be interpreted as a pure mechanical-damage coefficient unless the groups are otherwise comparable and the control captures the relevant non-cyclic influences.

A larger design can distinguish stress cycling, fluid exposure, and their combination. Preserve specimen identity and analyze contrasts at the specimen level. Repeated readings on one control improve the description of that control but do not replace independent controls. The water-damage literature motivates retaining exposure history [3], while contact models motivate mechanical observations [1]. Together they support a design that tests competing explanations rather than assigning every late-time loss to the loading excursion.

Interpreting hysteresis and testing memory

Hydraulic loops and surface observations

One possible descriptive measure is the area between loading and unloading conductivity curves over a shared stress interval. This area has units of conductivity multiplied by stress. Dividing it by the initial conductivity and the interval width gives a dimensionless index. The sign convention, interpolation procedure, and shared interval must be specified, especially when the branches were measured at different stress steps.

This index is not mechanical energy dissipation. Mechanical work requires force-displacement or stress-strain information with an appropriate geometry. A conductivity-stress loop instead summarizes hydraulic path dependence. Two loops with the same area can have different endpoint recoveries, and two specimens with the same recovery can have different loop shapes. The proposed index should therefore supplement, rather than replace, absolute endpoint measurements.

Before calculating an area, check that the curves use the same phase and pressure convention and that the apparent loop exceeds measurement uncertainty. Unequal dwell times can introduce a time-dependent contribution. Contact-mechanics studies provide a context for irreversible deformation [1, 2], but a loop in hydraulic data alone cannot establish plasticity, creep, or chemical alteration as the sole cause. The distinction prevents an attractive summary statistic from becoming an unsupported mechanism claim.

Hydraulic hysteresis can motivate a search for irreversible changes, but a conductivity curve does not directly reveal the contact geometry. A proposed companion measurement follows displacement or surface topography at documented states. If an imaging method requires unloading or disassembly, that intervention becomes part of the history and may prevent direct observation of the loaded configuration. State this limitation instead of labeling an unloaded image as a picture of the peak-stress contacts.

Compare observations that can discriminate among explanations. A persistent displacement change, a modified surface profile, and reduced return-state conductivity together support a different interpretation from reduced conductivity with no resolved geometric change. The latter result does not prove that geometry was unchanged; it may indicate insufficient spatial resolution or a change outside the measured region. Embedment and rough-contact studies motivate these candidate observations [7, 9], not a unique inversion from one flow curve.

The analysis should preserve uncertainty in coordinate registration, instrument compliance, and the hydraulic conversion. If the surface measurement and flow measurement disagree, investigate the mismatch rather than selecting the more convenient observation. A coherent interpretation

explains which aspects of the data are directly observed, which are model-derived, and which remain hypothetical. That distinction is essential when a cyclic result is later used to justify a constitutive memory variable in a larger model.

Tests that can reject a recovery model

State the hypothesis narrowly. For example, test whether returning to the initial effective stress restores conductivity within a prespecified tolerance at a specified time. The tolerance should reflect measurement capability and the decision being supported. It should not be selected after the result is known. If the experiment is too imprecise to distinguish the tolerance, the outcome is inconclusive rather than evidence of full restoration.

A stronger design compares the cycled specimen with an uncycled, time-matched reference. If both lose conductivity, part of the change may be associated with time or exposure rather than the stress excursion. If only the cycled specimen loses capacity, the excursion becomes a stronger candidate, although initial specimen differences still matter. Preserved material and controlled support geometry improve the interpretability of this contrast [10, 14].

For reporting, provide the three absolute conductivities, all recovery definitions, measurement times, and the independent specimen count. Describe any lost readings or apparatus interruptions. A useful conclusion identifies the loading interval over which recovery was tested and the uncertainties that remain. This produces a reproducible statement about reversibility without claiming that a short laboratory cycle reproduces every field pressure fluctuation.

A reversible conductivity function of current stress has no information about earlier maximum stress. To represent different loading and unloading values at the same stress, a model must carry an additional state description or use separate branches. Possible descriptors include cycle number, maximum previous stress, or a measured irreversible displacement. These are candidate representations, not interchangeable physical explanations, and the available experiment may constrain only some of them.

A proposed validation uses one loading history for parameter estimation and another for prediction. For example, a model fitted to one large cycle can be asked to predict a smaller subsequent cycle without resetting its state arbitrarily. Report whether the starting condition for the prediction was measured or inferred. If the model needs a new fitted parameter for every cycle, agreement with the observations does not establish transferable memory behavior.

The model should also preserve the distinction between mechanical and exposure history. Returning stress to an earlier value does not reverse a fluid treatment or restore an altered surface automatically. The most useful outcome may be a bounded set of state-dependent curves rather than one universal recovery law. Such a set can identify where predictions are supported and

which additional history would provide the most discriminating test. This is a proposed route from repeatable cyclic observations to an explicit, testable description of path dependence.

Implications for operations

A pressure increase during shut-in may reduce effective closure stress, but the laboratory evidence does not justify assuming complete restoration of earlier flow capacity. Conversely, incomplete recovery does not by itself establish that a field treatment is unsuccessful. The useful output is a measured loading-unloading trajectory with time and exposure controls. This note proposes a reporting framework and a synthetic example; it reports no new cyclic experiments and makes no field recovery forecast.

References

Numbered references correspond to the citations in the text. Links lead to DOI records or the identified source record.

- [1] Wu, W.; Sharma, M. M. (2017). A model for the conductivity and compliance of unpropped and natural fractures. *SPE Journal*, 22(6), 1893-1914. <https://doi.org/10.2118/184852-PA>
- [2] Barton, N.; Bandis, S.; Bakhtar, K. (1985). Strength, deformation and conductivity coupling of rock joints. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 22(3), 121-140. [https://doi.org/10.1016/0148-9062\(85\)93227-9](https://doi.org/10.1016/0148-9062(85)93227-9)
- [3] Zhang, J.; Zhu, D.; Hill, A. D. (2016). Water-induced damage to propped-fracture conductivity in shale formations. *SPE Production & Operations*, 31(2), 147-156. <https://doi.org/10.2118/173346-PA>
- [4] Kakkar, P. (2016). Experimental study of the effect of stress and fluid sensitivity on propped and un-propped fracture conductivity in preserved reservoir shale. *Thesis, The University of Texas at Austin*. <https://www.pge.utexas.edu/pge-research/2016/>
- [5] Wu, W.; Kakkar, P.; Zhou, J.; Russell, R.; Sharma, M. M. (2017). An experimental investigation of the conductivity of unpropped fractures in shales. *SPE Hydraulic Fracturing Technology Conference and Exhibition, SPE-184858-MS*. <https://doi.org/10.2118/184858-MS>
- [6] Wu, W.; Zhou, J.; Kakkar, P.; Russell, R.; Sharma, M. M. (2019). An experimental study on conductivity of unpropped fractures in preserved shales. *SPE Production & Operations*, 34(2), 280-296. <https://doi.org/10.2118/184858-PA>
- [7] Zhang, J.; Ouyang, L.; Zhu, D.; Hill, A. D. (2015). Experimental and numerical studies of reduced fracture conductivity due to proppant embedment in the shale reservoir. *Journal of Petroleum Science and Engineering*, 130, 37-45. <https://doi.org/10.1016/j.petrol.2015.04.004>
- [8] Wen, Q.; Zhang, S.; Wang, L.; Liu, Y.; Li, X. (2007). The effect of proppant embedment upon the long-term conductivity of fractures. *Journal of Petroleum Science and Engineering*, 55(3-4), 221-227. <https://doi.org/10.1016/j.petrol.2006.08.010>
- [9] Wang, H.; Sharma, M. M. (2017). A non-local model for fracture closure on rough fracture faces and asperities. *Journal of Petroleum Science and Engineering*, 154, 425-437. <https://doi.org/10.1016/j.petrol.2017.04.024>
- [10] Jung, C. M.; Zhou, J.; Chenevert, M. E.; Sharma, M. M. (2013). The impact of shale preservation on the petrophysical properties of organic-rich shales. *SPE Annual Technical Conference and Exhibition, SPE-166419-MS*. <https://doi.org/10.2118/166419-MS>
- [11] Jansen, T. A.; Zhu, D.; Hill, A. D. (2015). The effect of rock mechanical properties on fracture conductivity for shale formations. *SPE Hydraulic Fracturing Technology Conference, SPE-173347-MS*. <https://doi.org/10.2118/173347-MS>
- [12] Zhang, J.; Kamenov, A.; Zhu, D.; Hill, A. D. (2014). Laboratory measurement of hydraulic-fracture conductivities in the Barnett Shale. *SPE Production & Operations*, 29(3), 216-227. <https://doi.org/10.2118/163839-PA>
- [13] Zhang, J.; Kamenov, A.; Zhu, D.; Hill, A. D. (2015). Development of new testing procedures to measure propped fracture conductivity considering water damage in clay-rich shale reservoirs: An example of the Barnett Shale. *Journal of Petroleum Science and Engineering*, 135, 352-359. <https://doi.org/10.1016/j.petrol.2015.09.025>
- [14] Wang, J.; Elsworth, D. (2018). Role of proppant distribution on the evolution of hydraulic fracture conductivity. *Journal of Petroleum Science and Engineering*, 166, 249-262. <https://doi.org/10.1016/j.petrol.2018.03.040>