Investigating Stiffness Controls on Earthquake Behavior – An Ideal Environment for Python Workflows

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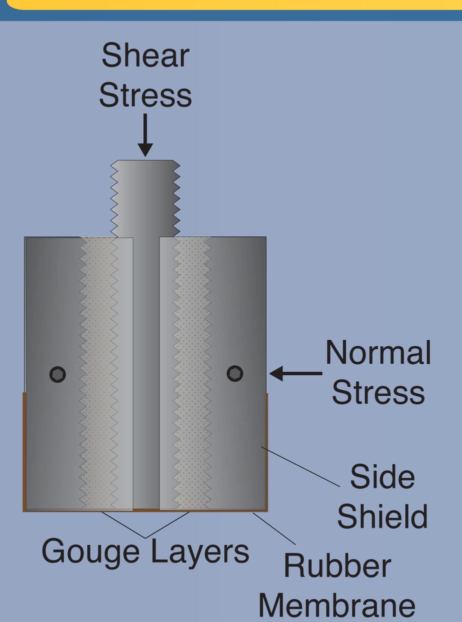
Introduction

Rock mechanics consists of studying the behavior of natural and synthetic faults and applying this knowledge to earthquakes. The large, high resolution datasets generated by such experiments are often not shared in their raw format and many parameters are analyzed by hand. Our laboratory is producing new tools and techniques to share with the community of researchers in an open source framework.

Studying natural and synthetic materials informs our understanding of how natural faults fail and produce a wide spectrum of energy release events. Recent studies have shown that the stiffness of the system can be a controlling mechanism to determine if earthquakes or slow-slip/creep events released stored elastic energy. Some tools exist for interpreting laboratory results, but they are rapidly becoming obsolete as most users are no longer developing the tools. Our goal is to produce a community set of modeling and interpretation tools to be used by our laboratory and others. We further wish to reduce analysis time by automatizing tasks that were previously done by hand.

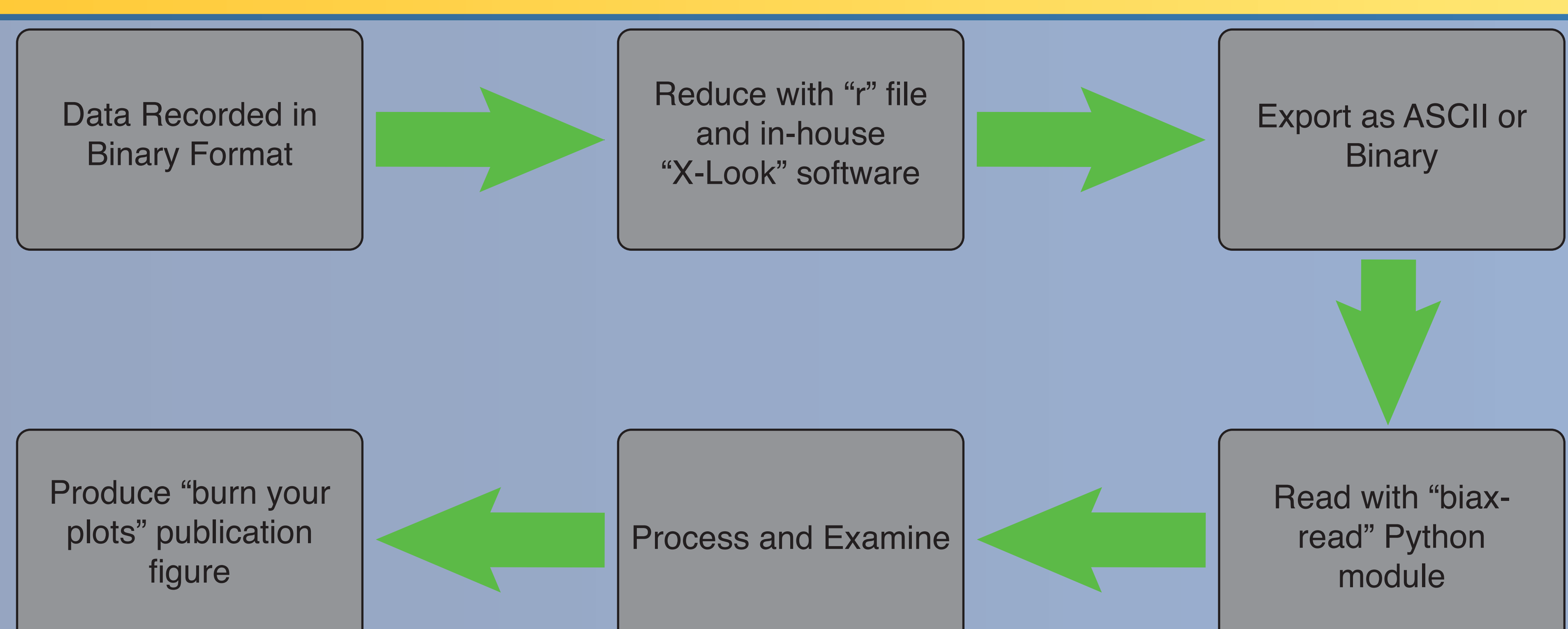
Experimental Setup



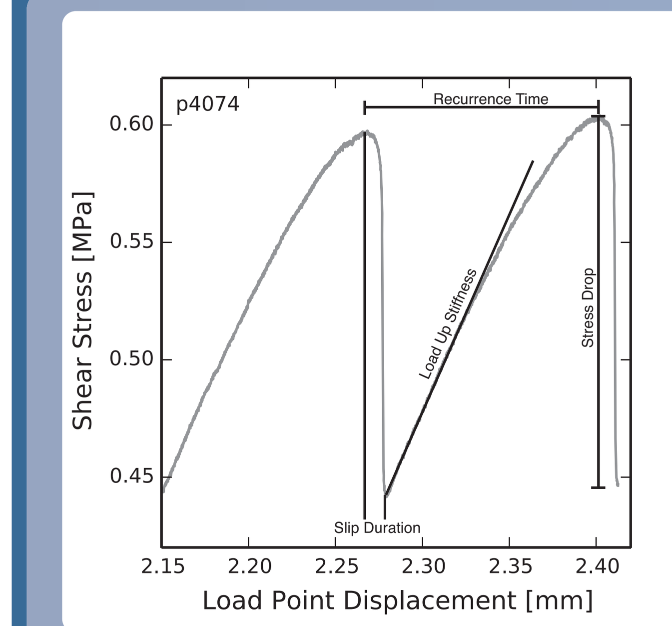
Our experiments take place in a "double direct shear" geometry, in which we shear two granular layers with a large servo-controlled hydraulic press. We shear both natural and synthetic fault gouge, measuring the displacement and force on both axes of the press system. A constant normal stress is maintained while the system is sheared at a constant displacement rate. Data are recorded at 1-10,000 Hz, depending on the experimental configuration. Currently all control is accomplished with analog electronics and recording is done with LabView. We are continually improving and updating the control hardware and have begun testing a tool to create control profiles with Python.

We have recently experimented with varying the apparatus stiffness by using forcing blocks made of various materials (steel, acrylic, UMHW plastic, etc).

Data Flow



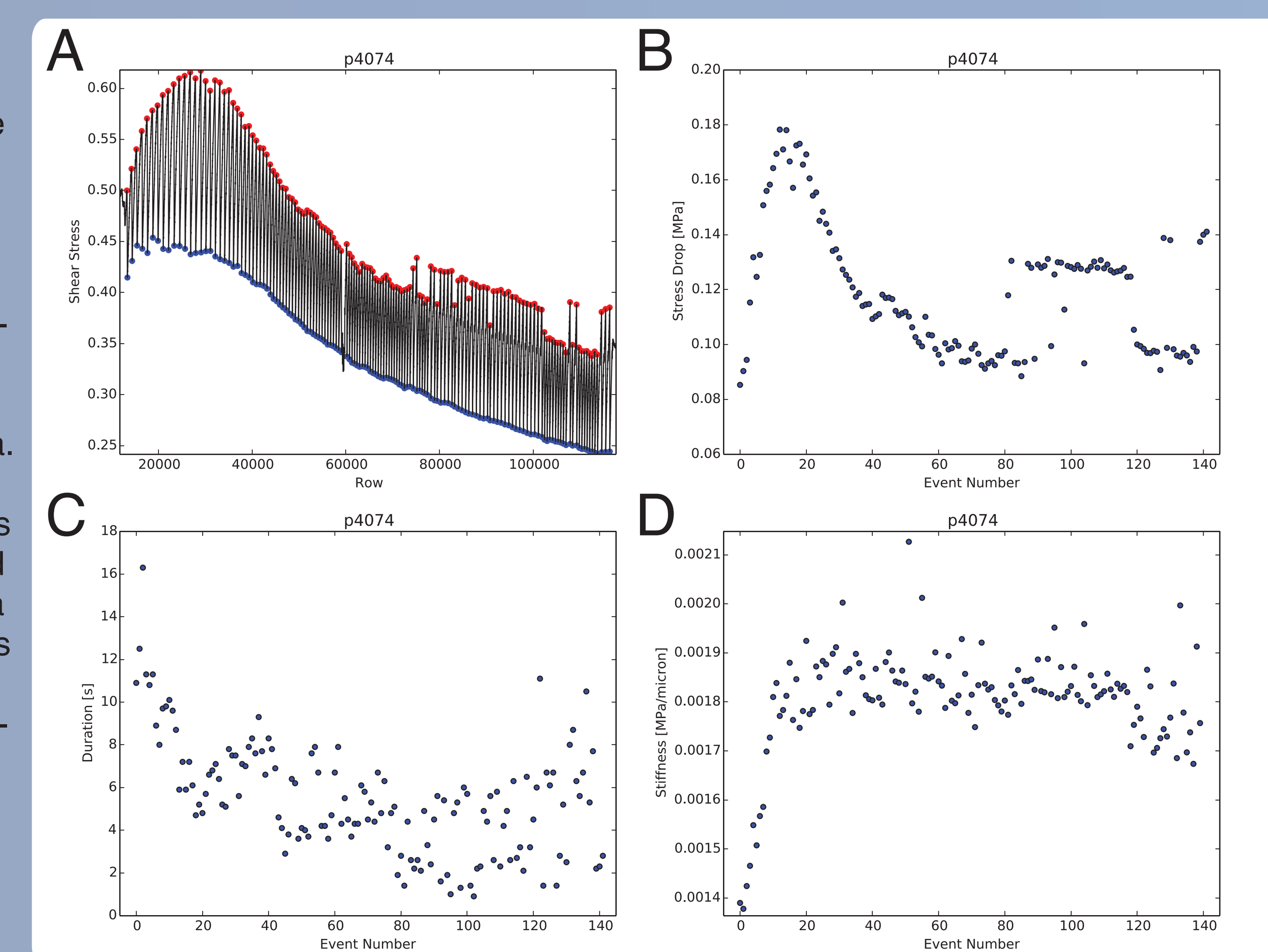
Applying Python

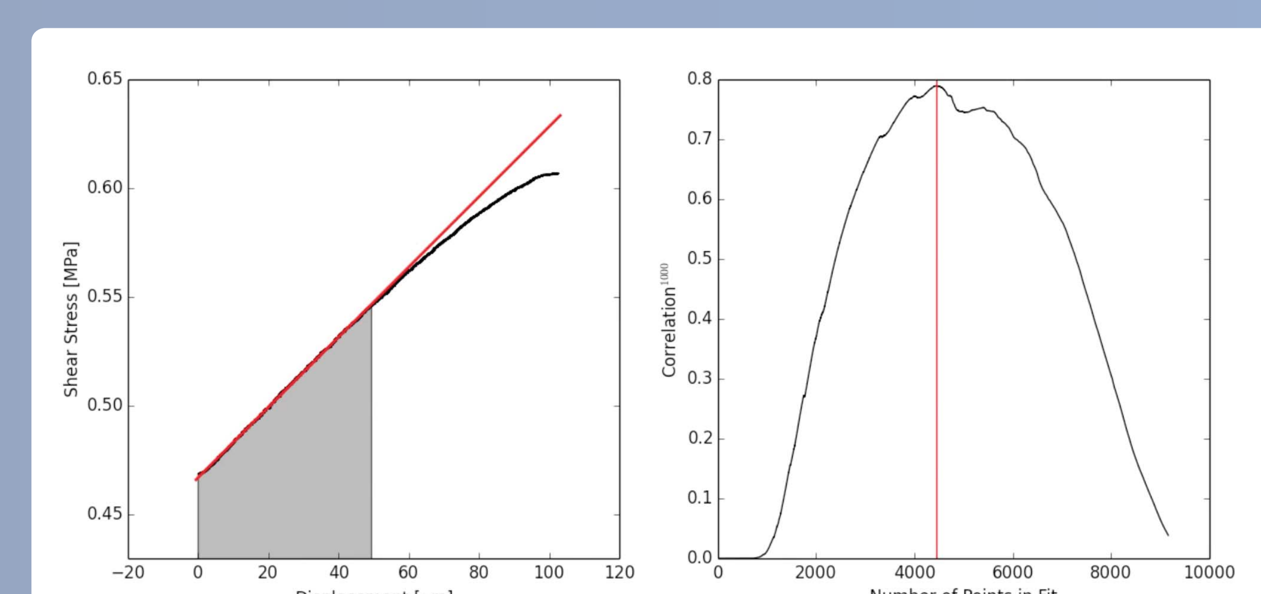


The earthquake cycle in the lab and in nature consists of the storage of strain energy in an elastic medium until the stress reaches the ultimate strength of the material. We often discuss the events in terms of the time between them (recurrence time), the energy release (stress drop), how long the event was (slip duration), and the system loading stiffness.

In the past, experimentalists would hand pick these values for hundreds of events. Python has provided a platform for the development of algorithms to automatically analyze these quantities (and others). Challenges remain in handling data that changes recording rates over orders of magnitude during a single experiment and filtering noise while preserving peak position and amplitude.

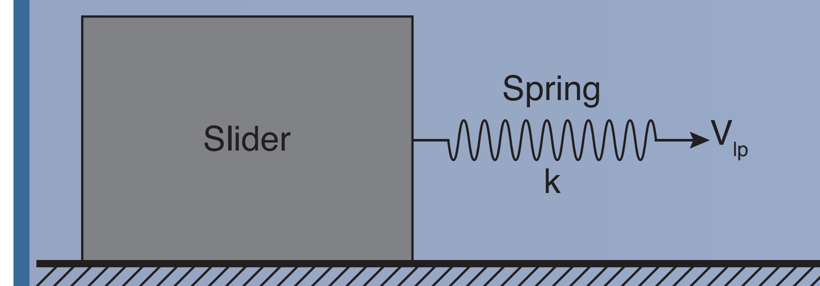
Stick-slip events can be picked automatically by calculating the derivative of the shear stress and finding the zero-crossings (inflection points). Noise in actual data makes this more difficult, and we chose to implement a running average slope with a simple least squares misfit to a small window of data. After maxima/minima are picked and paired, small events (remaining noise) are threshold filtered. The final result (A) is a clean series of picks. From this data, quantities such as stress drop (B), slip (co-seismic) duration (C), and stiffness (D) can be calculated. Stiffness is slightly more complex (below).





Determining the linear-elastic stiffness of each stick-slip requires fitting a line to the displacement versus shear stress data, but only to the portion before plastic deformation and creep begins. In the past this has been done by eye and resulted in limited estimates of stiffness for each experiment as well as inconsistency between picks. To automate this process, we calculate the correlation coefficient of the data for many data windows. The algorithm begins with the trough point picked by the derivative technique and calculates the correlation of three data points (the trough and the two subsequent points). Next, the correlation for 4,5,6,...,n data points is calculated. We assume that where the correlation is maximized, the deviation from linear-elastic behavior begins. A minimum of three data points are required since any two data points will have a correlation of unity and mis-guide the algorithm. After the number of data points that maximize correlation is found, a line is fit to that data segment by a least squares method. This process is repeated for each load up segment of the stick-slip/slow-slip events. The figure above shows the result of the stiffness picker on one load up curve.

Rate and State Frictional Models



Next tasks include completion of a rate and state modeling tool that is based in Python. Challenges include solving the set of stiff equations in such a way that we can solve at points for which we have experimental data. This allows inversion through techniques such as singular value decomposition (SVD) or with new techniques such as the covariance matrix adaptation evolutionary strategy (CMAES).

Rate and State Equation

$$\mu = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)$$

1-D Stiffness Coupling

$$\frac{d\mu}{dt} = k\left(V_{lp} - V\right)$$

State Evolution Law

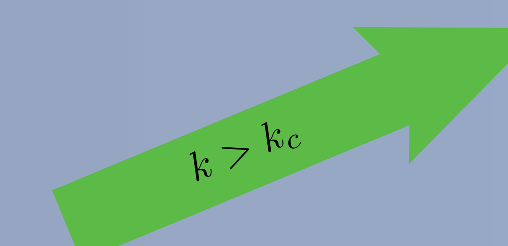
$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$$

Final Differential Equation

$$\frac{d\mu}{dt} = k\left(V - V_0\exp\left[\frac{\mu - \mu_0 - b\ln\left(\frac{V_0\theta}{D_c}\right)}{a}\right]\right)$$

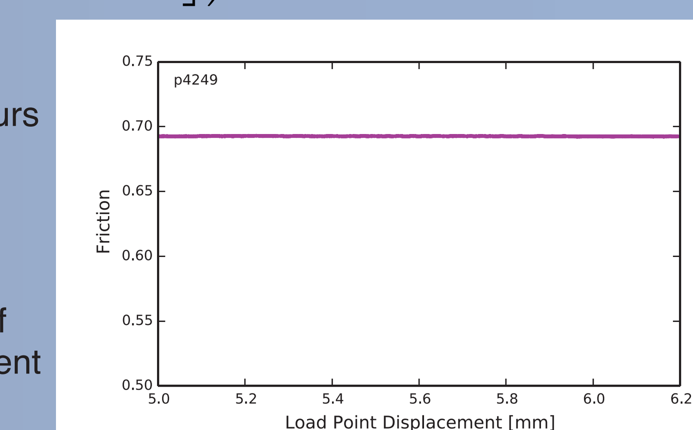
Critical Stiffness Hopf Bifurcation Point

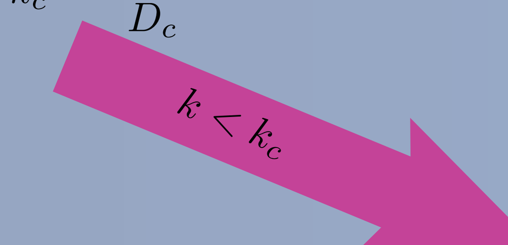
$$k_c = \frac{b-a}{D_c}$$



Stable Sliding (Creep)

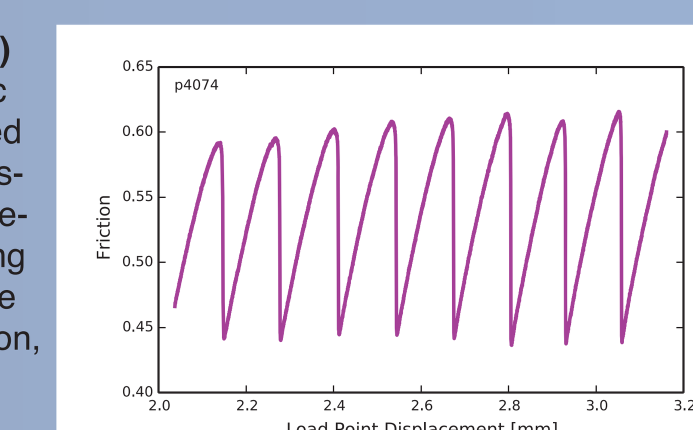
Stable sliding, or creep, occurs in stiff systems and is analogous to a fault that does not host major earthquakes. In these systems we can measure the velocity response of friction and the time dependent healing behavior.

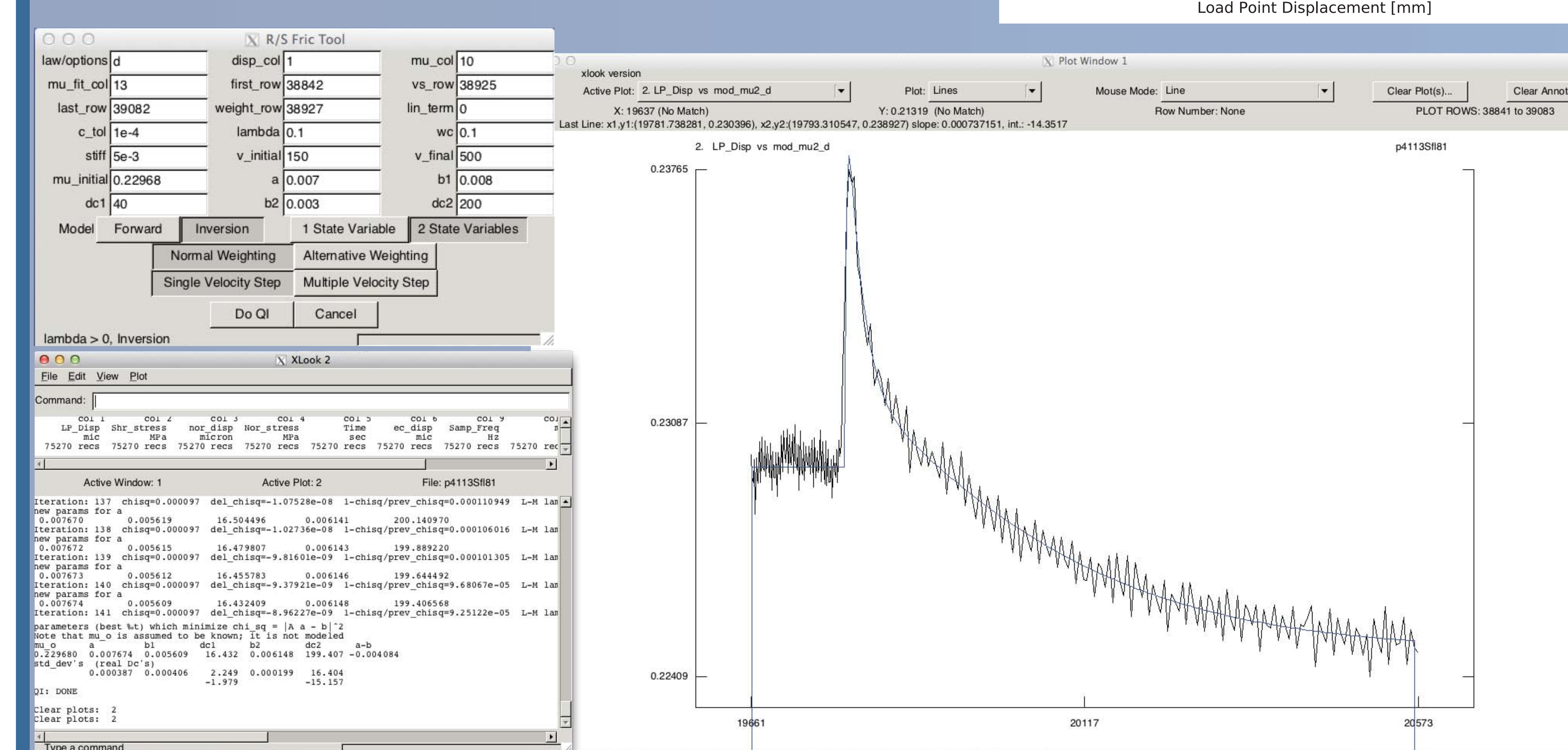




Stick-Slip (Earthquakes)

In compliant systems, elastic energy is stored and released in a way the may radiate seismic energy. This behavior depends on the frictional healing properties of the material, the velocity dependence of friction, and the stiffness.





Current inversion methods require an arbitrarily close initial model and are initial model dependent. Replacing this with a more sophisticated inversion routine should greatly reduce the time required to process and model data from an experiment.

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