GAINING INSIGHTS INTO IMPACT EVENTS THROUGH RHEOLOGY REGIME TRACKING.

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Introduction. We introduce a method for tracking the rheological regimes active throughout crater simulations resolved in both time and space. Using this method, we are able to watch the evolution of dominant rheology from the shock front moving through the target through to crater collapse and modification. This 4D view of cratering will be used to inform future model development, laboratory-based tests, and comparisons to field observations.

The rheology dominant at different stages of impact events determines the final morphology of the crater or basin. However, it is difficult to discriminate rheology dominant during the intermediate stages of impact events based on the observable morphology. Though multiphysics codes are central in the study of dynamic events, linking the physics responsible for observable features, including melt, central peak, and ring characteristics, is not straightforward.

Differences in the activation of rheology, where each dominates, and for how long, affects the observable features in ways that can be used to test and improve the physical models. Understanding these effects is important for discriminating between physical models that result in comparable final crater morphologies (e.g. [1], acoustic fluidization [2], and strain rate weakening [3] are methods of accounting for weakening and weakened deformation mechanisms). These models generate different stresses, peak pressures, melt, and bulk debris flows over time.

Shock-physics codes are vital for the study of impact events. However, capturing the interplay of physics implemented and how they interact has not been well studied.

Methods. We implement material variables to track the activation of implemented rheology regimes, throughout an impact cratering simulation. These regimes are weakening mechanisms that are activated by different physical processes. We want to systematically record which rheology regimes are called while the target material experiences compression and deformation in time and place.

Development of this method is done within a package of the shock-physics code CTH that has multiple rheological models implemented. Previous work has expanded these models to include a rheology model capable of accomodating rock deformation during impact simulations. The model is referred to as the 'Rock Model'.

The Rock model builds on the strength model outlined in [1]. The Collins, et al Yield critera model describes the yield surface for intact and damaged rock and includes thermal weakening[1]. Either the yield surface or Peierl's stress determine the yield stress a parcel of intact material. Once damage begins to accumulate, the material response follows one of three modes of solid deformation, strain rate weakening [3, 4], strain rate weakening with melt along the faults, or a Byerlee rock friction [5]. If the material has sufficient energy to melt or vaporize, it behaves accordingly.

When the material is initialized, it is assigned an integer regime flag variable that is updated during the calculations within the Rock rheology model. A unique integer regime flag is assigned to each decision branch in the code, which results in a history of the dominant rheology at that point and time. Once a failure threshold is met, the flag records that failure mechanism, which is then updated based on the constitutive law responsible for the deformation of the now damaged material.

Systematically testing impact simulations. Regime tracking has been tested in both 1D and 2D models. The sampling of physical regimes by material parcels has been tested in both 2D axially symmetric simple and complex impact simulation and within 1D planar shock simulations. The simple tests are designed to isolate different processes within the rheology model.

Through tracking the rheology dominant through impact events, we study the reliability of simulated impact outcomes. We are building model diagnostics that expand on this 4D tool to quantitatively study the deformation mechanisms activated in time during impact events. In our study, we can compare simulations that include or exclude different physical processes. With this, we can observe the affects of changes in the assumed rheology models and discriminate between the observable features generated by different specific processes.

From this 4D look at impact events, we 'zoom in' on specific regimes activated in space and time to reproduce the regime in simplified tests. 'Zooming in' on a specific parcel of material links the large scale impact simulation with much simpler, computationally inexpensive 1D models. This links the behavior of the model in simple simulations directly to computationally expensive simulations, making the outcomes of verification, validation, and benchmarking studies directly and clearly relevant to the impact events.

Systematically testing the activated rheology includes the development of a suite of benchmarks that test

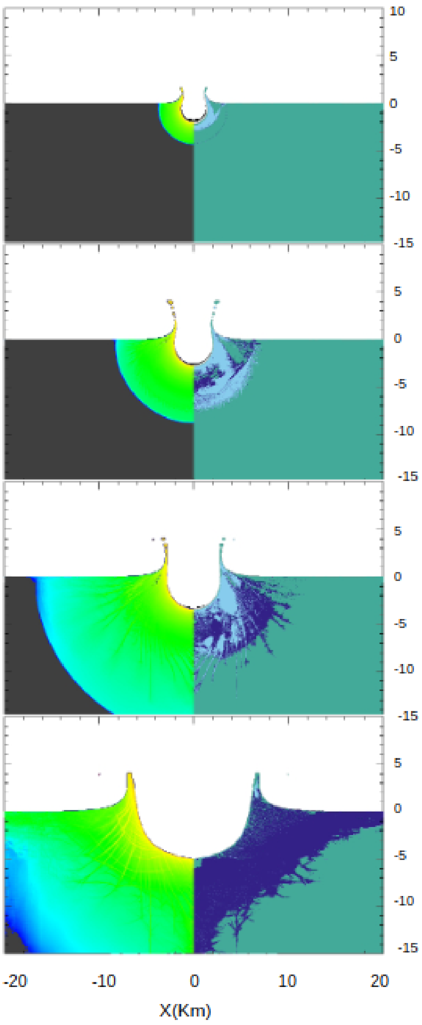
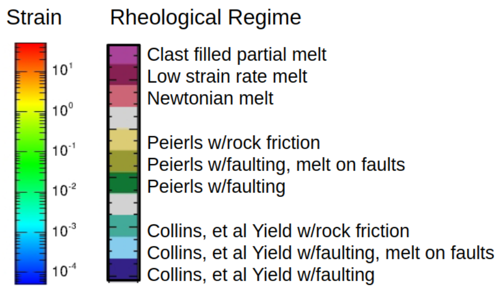


Figure 1: Total acucmulated plastic strain (left) and rheology regimes activated (right) in a simple impact simulation at 0.5, 1.3, 2.8, and 13 seconds after impact. This is a 1-km basalt impactor into a basaltic crust under lunar gravity.

each regime. Looking forward, we can determine the reliability of simulated outcomes based on the conditions under which parcels of target material enter different rheologies.

Gaining physical insight from 4D data. Regime tracking allows us to gain intuition into the mechanisms that determine the final crater morphology. Testing and comparing physics between models as well as comparing differences in simulated outcomes when rheology is activated allows us to isolate the rheology responsible for the formation of specific, observable features.

Through tracking when regimes are activated and where, we also determine the amount of relative power each rheology has during an impact simulation. This diagnostic provides insight into which regimes dominate in simulations and where to focus future development and validation efforts.



Conclusions. Impact models must be capable of handling a broad range of rheological regimes. The cumulative effects of traversing through these various physical processes determines the simulated outcome of observable features. However, determining which rheology is responsible for observable features and how to discriminate between models that can describe the observed behavior is challenging.

Though challenging to visualize and analyze, animations of the time evolution of regime activation and physical properties such as yield strength or friction coefficient provide modelers with additional intuition of cratering mechanics and spatial maps of dominant processes. The time history of deformation for tracer particles or SPH particles as well as benchmark tests can be compared between codes and for extraction and comparison to experimental studies and field observations.

In building simple tests and methods of visualizing the evolution of rheology dominant throughout the cratering process, we intend to provide impact modelers with a means of building intuition about impact events as well as provide a basis for verification of physics packages within their codes, validation of their codes, and comparison between available models.

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