Summary of Session on Rock Properties that Need to be Known for Theoretical Modeling, Friday, February 7, 10:15 a.m.

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Introduction

Material properties are a fundamental component of impact cratering studies, influencing any part of the cratering process and its results. Specific material properties govern the response of material to stress, resulting in different behaviors of different materials for nominally the same impact conditions. This has been long recognized, as is witnessed by the long list of publications devoted to understand the response of material to shock events through both laboratory and field investigations. Yet, the general feeling is that we still do not have enough information to be able to completely characterize the behavior of material during the impact cratering process. From the modeling point of view, modeling of material behavior is the still biggest shortcoming in code calculations, and the primary reason for bad results. It is thus not surprising that this is the topic of the very first session of this workshop.

Rock Properties that Need to be Known to Model Impact Processes

The session was opened by the invited talk of Keith Holsapple, who gave an overview of the data that laboratory and explosion tests have provided over the years, as well as a discussion of the main material models used in impact cratering modeling studies, and their limitations. Theoretically, material behavior during an impact can be divided into three regimes: P>> c^2 (is material density, c the sound velocity, and P is pressure), which corresponds to the contact and compression stage (when material is subject to a strong shock), and is governed by the equation of state; P~ c^2, which roughly corresponds to the crater formation stage (post-shock state), and is governed by the constitutive (stress-strain) equation; and P<< c^2, which is characterized by fractured material whose behavior becomes similar to a fluid, and is governed by fracture and damage models.

The equation of state (EoS) is fundamental in modeling the initial response of material to very high pressures, and in particular, the amount of melting and vaporization of target and impactor material. There is a large body of data available in the literature for material response to high shocks. It includes measurements of the Hugoniot state of material and some shock unloading data (adiabats), as well as static melt and vapor points at atmospheric pressure, specific heat, thermal expansion, and critical point measurements. However, there are still many regimes (P-T) in which we really have no data, and thus we must extrapolate with models from the regimes that are better known. Various different kinds of EoS have been used for impact modeling, ranging from analytical, single phase simple models, such as Murnaghan (non-linear elastic, no thermodynamics), Tillotson (powers in density + thermal component + vapor interpolation), and Mie-Gruneisen (linear shock-particle velocity relation + thermal component + vapor interpolation), to semianalytical, multiple phase complex models such as ANEOS and PANDA. The best approach to EoSs in wave codes is that of using tabular forms, such as the SESAME tables, that can use real data; the only problem is that for some ranges of pressure and temperatures, and for many materials of geologic interest, the tables are reconstructed from models, and thus contain the same limitations. In addition, most materials occur in nature as a mixture, and with different levels of porosity (affecting pressure decay in the material), which adds yet another level of uncertainty to the modeling, and one which has not been investigated as thoroughly as needed. In summary, although the tools are there for complex EoS models, it is very hard to get the data necessary to calibrate the models.

The constitutive equation, which describes the response of a material to stresses that induce deformation, is even tougher to deal with. Modeling it correctly would allow us to reproduce the final size and shape of an impact crater. Unfortunately, models are still limited by the lack of adequate data as well as the difficulty of scaling laboratory results (small scale, both spatial and temporal) to planetary scale events. Constitutive models used so far have difficulties in modeling adequately what happens when a material reaches the failure limit and starts bulking. Material becomes fractured and unable to resist stress. This has been parameterized in models as 'damage,' which is used to modify the cohesive strength of the material. A number of strength models have been formulated over the years, like von Mises, Mohr-Coulomb, Drucker-Prager, which do not include damage. An improved model, which also includes damage, is that of Johnson and Holmquist. Even this model, however, has limitations, most notably the lack of temperature dependence. An alternative model that has been used is the Grady-Kipp, which uses a degraded stiffness concept. The 3D version of this model has been rather popular and has attractive physics, but this model too has limitations, such as the assumption of isotropic damage, and a zero shear stiffness limit, which reduces the material to a water-like behavior. Again, there is the need of performing a lot more laboratory testing of materials and comparison of the model to real data (both laboratory and explosion, when available) to constrain the parameters used in constitutive equations.

In summary, there are still many shortcomings to correct modeling material behavior during an impact event. Unfortunately, the need for publication as a way to show productivity often causes the testing and comparison phase to be barely addressed, if not totally bypassed. This results in a general lack of objectivity when looking at modeling results, ranging from total disbelief to a complete trust of anything coming out of a model.

Rock Properties that Can be Inferred from Field Studies of Impact Structures

The advantages and limitations of field studies to infer rock properties were addressed in John Spray's invited talk. It is important to remember that field observations essentially correspond to an "autopsy" of what is left behind by an impact process. Geologists then try to reconstruct what happened from those observations. The work of a geologist is made even more difficult by the terrestrial environment, where continuous erosion and sedimentation, as well as tectonic deformation act to delete some of the features that are so clearly observed on other planetary bodies, making the work of identifying key parameters, like the crater rim, much more complicated. Furthermore, material properties change during the impact process; a geologist only sees its end result, a modeler will have to start from the initial conditions. Ideally the two approaches (forward for the modeler, backward for the geologist) should give the same answers.

In doing fieldwork a geologist looks at specific outcrops, and his observations are usually at the cm-m scale. Outside the main melt sheet, what is observed in the rocks is the presence of regions of concentration of friction melt, also called pseudotachylites. These regions occur all over the impact region, and show variations in characteristics. In the innermost zones, the friction melt is present as small veins (cm-scale) occurring at intervals of few tens of cm, and showing small displacements (few mm at most) with the rock in between being completely coherent. These are classified as S-type pseudotachylites. This friction melt may contain high-pressure polymorphs, like cohesite and stishovite, and is believed to be shock-related. In the outer region of impact structures, melt friction ranges in thickness from cm to km, exhibits large offsets (up to km), and is generally associated with faults (not as a single big pseudotachylite, but as a complex of friction melts). High-pressure polymorphs are totally absent in these E-type pseudotachylites. Because of their association with faults, they appear to be driven by the gravitational collapse of the crater, and suggest a discrete deformation of the rocks.

Another impact rock feature that has been very useful to geologist in the characterization of impact structures are shatter cones. Looking at them on end, they show an interesting pattern of fractures with offset on them of 1 mm or so, and careful TEM observations indicate that they are coated by a thin layer of melt, indicating that their formation mechanism may be somehow similar to the formation of S-type pseudotachylites.

Putting it all together, this suggests that although the shock wave initially started of in a continuous hemispheric pattern, it would change into a more "broccoli" like pattern as it rips through the rocks becoming more and more distorted and setting up shear systems. Once the transient crater develops, gravity collapse will drive the formation of faults and the displacements in the rocks, with inter-radial and inter-concentric crack being filled by friction melt. This view does not seem to fully reconcile with modeling results of a continuous fluid-like motion of the rocks.

Conclusion

One thing that seems to have emerged from the presentations and discussions that started from this session, with the panel discussion, and continued throughout the workshop is the importance of the scale of the processes investigated. At the field geology scale, (centimeters to meters), deformation appears partitioned, discrete; there is no evidence in the modification stage of fluidization in the gross scale. On the other hand, at the modeling scale, (meters to hundreds of meters) the discrete nature of displacement is lost, in favor of a more homogeneous flow-like description of the process. This is where a big disconnect appear to occur between modeling and observations. The resolution allowed by the current computer power, does not allow to model the impact process at the scale investigated in the field. Thus, processes that appear to be discrete to a field geologist are necessarily described as continuous in a model, since the discrete process occurs on a scale much smaller than the allowed resolution of the model. Field geologists appear to have a problem with a "continuous flow" of material, as this is not really observed in the field. This causes much suspicion about models that use a material flow approach to explain the opening and collapse of impact structures. On the other end, in modeling large scale impacts modelers tend to neglect the small scale characteristics, as they cannot be addressed by current model resolutions. As Melosh pointed out in his invited talk, it is just not possible to model the opening of a huge impact crater like Chicxulub and expect to model microscopic processes, in the same calculation. This limitation also applies to other problems that were touched upon during the panel discussion session, like mixing of the melt sheet, and formation of tektite strewn fields. It is very important for geologists to understand the limitations of modeling work, and be aware of both advantages and disadvantages of the models. This implies that modelers must be very clear on model assumptions and their limitations. On the other hand, it seems that fieldwork has not concentrated much on the type of information that a model could indeed address. This is directly related to an important limitation field geologists have to deal with: the lack of adequate funding for systematic fieldwork at impact structures. They are thus forced to pick what they think are type locations for detail investigation. Unfortunately, has was pointed out by Sharpton in his invited talk, this also means that those type localities must be picked on the basis of a pre-conceived "model" that a geologist must have of the impact process, and what are the important features. This means that "observations" are usually biases a priori by models, and are interpreted through the prism of that preconceived interpretation.

In summary, this section has pointed out that: 1) even after decades of studies, our understanding of material properties is still limited, and much more experimental work is needed to characterize efficiently the parameters that are normally used in constructing material models; 2) both modeling and observation approaches have limitations; disregarding the results of one or the other approach can only be detrimental to our understanding of impact cratering. It has become clear from the whole workshop that only if both modelers and observationalists develop some understanding of the other approach we can hope to combine the results of both type of studies to reach a full understanding of impact cratering.