INTRODUCTION

On February 7–9, 2003, approximately 60 scientists gathered at the Lunar and Planetary Institute in Houston, Texas, for a workshop devoted to improving knowledge of the impact cratering process. We (co-conveners Elisabetta Pierazzo and Robert Herrick) both focus research efforts on studying the impact cratering process, but the former specializes in numerical modeling while the latter draws inferences from observations of planetary craters. Significant work has been done in several key areas of impact studies over the past several years, but in many respects there seems to be a disconnect between the groups employing different approaches, in particular modeling versus observations. The goal in convening this workshop was to bring together these disparate groups to have an open dialogue for the purposes of answering outstanding questions about the impact process and setting future research directions. We were successful in getting participation from most of the major research groups studying the impact process. Participants gathered from five continents with research specialties ranging from numerical modeling to field geology, and from small-scale experimentation and geochemical sample analysis to seismology and remote sensing.

With the assistance of the scientific advisory committee (Bevan French, Kevin Housen, Bill McKinnon, Jay Melosh, and Mike Zolensky), the workshop was divided into a series of sessions devoted to different aspects of the cratering process. Each session was opened by two invited talks, one given by a specialist in numerical or experimental modeling approaches, and the other by a specialist in geological, geophysical, or geochemical observations. Shorter invited and contributed talks filled out the sessions, which were then concluded with an open discussion time. All “modelers” were requested to address the question of what observations would better constrain their models, and all “observationalists” were requested to discuss how their observations can constrain modeling efforts.

To enhance the long-term benefit of the workshop, a number of items are included within this technical report:

- Workshop program and abstracts.
- Summaries of each session: Members of the advisory committee were asked to summarize one of the sessions.
- Transcripts of selected parts of the workshop: The co-conveners attempted to audiotape the workshop. Transcriptions of some of the talks and all the discussion sessions (at least all that we didn’t foul up the taping for) are included. [The majority of talks given during the workshop utilized computer-generated slide presentations. Many speakers presented us with a digital version of their talk. We have organized these and they are available on the meeting Web site (www.lpi.usra.edu/meetings/impact2003/), but they are not formally included as part of the technical report.]
- List of workshop attendees and their affiliations as of the time of the workshop.

Also provided is a brief overview of the workshop, and the recommendations for future studies that came out of the talks and discussion sessions.
WORKSHOP OVERVIEW

The Friday morning session opened with two keynote talks scheduled. Jay Melosh gave an overview of the state of knowledge of numerical modeling efforts, outlining the limitations intrinsic to the modeling, and those imposed by current computational capabilities. Unfortunately, flight cancellations prevented the second keynote speaker, Richard Grieve, from attending the workshop. Robert Herrick filled in and presented an introductory talk divided into three components: constraints on the impact process from field studies of terrestrial craters, constraints from orbital observations of planetary craters, and primary unanswered questions in cratering mechanics. Transcripts of these talks and question session that followed them are included in this report.

After a break, the morning session continued with a session dedicated to “Rock properties that need to be known for theoretical modeling,” with an invited talk by Keith Holsapple summarizing the important material properties needed for accurate modeling of impact processes. Although current models use simplified representations of material properties, we have inadequate data to properly parameterize even those simplified models. John Spray followed with an invited talk focused on the effects of the impact process on geologic materials observed in terrestrial craters. He discussed the problems with field observations, and in particular focused on pseudo-tachytes. His observations indicate that pseudo-tachytes are intimately related to deformation of the post-excavation cavity, and the deformation associated with complex craters occurs in discrete zones. A panel-led discussion followed the two invited talks addressed various aspects of impact effects on rocks, including melting/vaporization, fracturing, and the fate of the material ejected in an impact. In particular, melt homogenization and the role of melt in crater formation are not well understood.

The Friday afternoon session, titled “Effects of target properties on the cratering process” was a logical continuation of the morning session in addressing how the macroscopic characteristics of the target can affect the final crater characteristics. Kevin Housen’s invited talk discussed what controlled experiments have taught us about the effect of different target properties on cratering efficiency. He surmised that the internal friction angle plays the most important role on cratering efficiency, followed by porosity. In particular, Housen emphasized the need for a set of benchmark experiments for code testing. In his invited talk, Paul Schenk used observations of planetary craters to highlight a variety of effects that different target properties have on complex crater formation. Target gravity, composition, and layering all have significant effects on the morphology of complex craters and the crater sizes at which complex morphologies occur. Two talks in the session (a short-invited talk by Jens Ormo and a contributed talk by Galen Gisler) discussed the unusual morphologies and other effects that result from oceanic impacts, where a fluid top layer is involved in the impact process. David Crawford showed some initial modeling of impact in a highly heterogeneous media. The final two contributed talks of the session, by Keith Holsapple and Gordon Osinski, discussed various aspects of impact melting. Holsapple concluded that it is nearly impossible to independently separate impactor size and velocity, even if you can reliably estimate melt volume. Osinski concluded that it is a myth that less melt is produced or preserved from impacts into sedimentary versus igneous targets. The lively afternoon discussion spilled over into the evening reception and poster session.

The Saturday morning session centered around “Thermodynamics of impact cratering and determining impactor characteristics.” Dugan O’Keefe opened the session discussing how to incorporate various thermodynamic effects into numerical modeling of craters. This invited talk was followed by the invited talk of Roger Gibson who presented an overview of the efforts to back out shock wave propagation and thermal histories for terrestrial impact craters. A major problem in these efforts is the extreme heterogeneity in shock effects at the outcrop and hand sample scale. Mike Dence’s short invited talk followed on with a discussion of field-observed shock damage that focused on Canadian craters. In the last short invited talk, Chris Koeberl presented an overview of the geochemical methods employed to determine the composition of the impactor. Uncertainties in asteroid and comet compositions, preservation of material over time, and how impactor and target materials mix all make this an extremely difficult problem, but progress is being made.

After the coffee break, a series of contributed talks explored various aspects of the session’s theme. Ahrens’ talk presented some specific model results that followed on O’Keefe’s earlier talk. Sugita discussed efforts to understand impact-induced vapor clouds from laboratory laser experiments. Gerasimov presented some of his work addressing the mixing of projectile and target materials, and Joeleht and
Newsom closed the session discussing post-impact hydrothermal systems for terrestrial and martian craters.

The Saturday afternoon session was devoted to “Ejecta emplacement and oblique impact effects.” The opening invited talk by Natasha Artemieva focused on numerical modeling of oblique impacts, particularly the earliest stages that could produce tektites or the SNC meteorites. Pete Schultz followed with an invited talk focused on his approach of relating small-scale experiments to observations of ejecta emplacement on planetary surfaces. He maintains that a detailed understanding of the response of an atmosphere to impact is needed for an accurate prediction of observed ejecta patterns on both Venus and Mars. Herrick presented a somewhat different approach of using observations of crater morphologies on the terrestrial planets to infer various aspects of cratering mechanics of oblique impacts. The last (contributed) talk before the break was a discussion by Anderson of possible modifications of the Z-model for the purpose of more accurately matching experimental observations and numerical models. After the break, Larry Haskin presented the results of modeling basin ejecta distribution to aid interpretation of lunar sampling and remote sensing data. The final talk of the day by MacDonald discussed mapping efforts of a remote Australian impact structure that may be the result of a rare case of a very oblique impact.

Cancellations of a few talks on Sunday allowed for more extensive and wide-ranging discussions during both the morning and afternoon sessions. Morning talks and discussions revolved around “Creation of the structure of complex craters.” Buck Sharpton began the morning with an invited talk discussing some of the problems of interpreting complex craters in the field. In particular, he cautioned against a “resonant feedback” down blind alleys, where models improperly guide field work and bias interpretations that are then used to confirm the model. He urged modelers to provide predictions that can be tested in the field, and geologists to focus on critical field observations that could be useful to modelers. Gareth Collins’ invited talk provided a summary of the state of the art of modeling complex crater collapse. He noted that the physics that controls this stage of crater development is very different from what occurs during the early stage of crater excavation. The initial conditions, or the state of the post-excavation transient cavity, are critical for a realistic model. All models of crater collapse require that a volume of material at least equivalent to the transient crater volume must be significantly weakened from its pre-impact strength. In the contributed talk before the break, Gordon Osinski presented some detailed fault mapping at Haughton crater, emphasizing that crater collapse at Haughton appears to have occurred primarily along discrete faults.

After the break, Bill McKinnon discussed constraints on scaling laws used to estimate transient crater diameter from orbital observations of large craters. Elisabeth Turtle presented a comparison of two different, and somewhat complementary, numerical codes that can be used to model crater collapse, as part of initial efforts to model the Silverpit structure. Jeff Plescia concluded the morning session talks with a discussion of the constraints on crater structure that can be learned from gravity data. The morning session ended with a discussion session.

The afternoon session had only three talks to allow for an extended final discussion session. The session was devoted to “Cratering on low-gravity bodies.” Clark Chapman’s invited talk began the session with a summary of observations from the handful of well-imaged asteroids. The most puzzling observations involve the unexpected presence of abundant regolith, its ability to organize into “ponds” and “beaches”, and the lack of the smallest-scale craters in that regolith. Eric Asphaug’s invited discussed cratering on asteroids from a modeling perspective, and he presented some lines of evidence that most asteroids are rubble piles. Naomi Onose concluded the session with an extended contributed talk discussing the results of some experiments designed to learn about ejecta behavior for low-g impacts.

The afternoon talks were followed by a general scientific discussion that transitioned into a discussion of future efforts. Much of the scientific discussion during the final session and throughout the workshop revolved around whether the nature of deformation observed in complex craters in the field could be reconciled with models. In the field, material movement seems to occur in zones of weakness along discrete faults, but craters are modeled with a continuum mechanics approach that has cell sizes of hundreds of meters. Many of the suggestions for future work presented below address this particular aspect of observations versus models.
FUTURE DIRECTIONS

A number of specific suggestions were made for future efforts from the impact community. Here, we summarize those that were met with general acceptance by workshop participants. In many regards the long-term benefit of the workshop depends on the level of successful implementation of these recommendations. They are as follows:

Create an Impact Cratering “List Serve”

To improve communication among the community studying impact craters, create a moderated email list serve that subscribers could use to notify others of data availability, discuss scientific issues, etc. Threads could be stored and posted on a web site accessible to the community and maintained by LPI.

Improve Data Archiving and Accessibility

It was acknowledged during the workshop that much of the data useful for impact studies is not readily accessible and/or was published in the gray literature. Only a few researchers know where to go to get access to explosion data that was generally collected for Defense Department purposes. Many detailed studies of impact and explosion craters were published as technical reports or in somewhat obscure regional journals. Only a small portion of laboratory experimental work has been published. Most field data, such as raw core descriptions, field notes, seismic data, etc., are not published.

Several approaches were discussed on how to make these valuable materials more accessible. It was suggested that we begin with a survey of workshop participants to determine who currently has different types of data, and in what form that data are accessible. Perhaps in conjunction with the list serve mentioned above, a web site could be developed that would be a central clearing house location for existing archival efforts. Examples of existing efforts include the database of terrestrial impacts that John Spray’s group maintains and an online bibliography of impact cratering references that Buck Sharpton’s group is working on. A data archiving and access enterprise that particularly appealed to many participants would be to centrally gather information regarding drill cores into craters: where the cores are located, access to samples, summary descriptions, etc. These types of efforts could be formalized and supported through the Planetary Data System as a node or subnode devoted to cratering, and it was suggested that the workshop organizers approach PDS regarding this possibility.

Develop Standardized Nomenclature

Some confusion continues to exist among researchers regarding definition of terms, and it was suggested that standardized nomenclature be developed. In the context of the topic of the workshop, there are discrepancies between how features are identified in computer models, on fresh craters in orbital imagery, and in partially eroded terrestrial craters. Examples include the boundary and nature of the central structure, how the crater rim is defined, and what is meant by crater size. No particular suggestions at how to approach this problem were made during the workshop, but perhaps a discussion of nomenclature could be developed as a subsidiary effort of the list serve and web site ideas.

Embark on a Few Focused Research Programs

A variety of suggestions for future research efforts were put forth during the workshop. A consensus began to develop for three broadly defined efforts that would be of particular benefit to the community:

1. Benchmarking and cross-comparison of hydrocodes currently used in impact cratering studies. Members of the modeling community that were present strongly advocated that a benchmark set of experimental and explosion crater data be developed and posted for the purpose of evaluating various numerical modeling codes. This benchmark data should encompass a wide range of impactor velocities and energies. A variety of targets should be used that have varying strength, porosity, layering, and so on. To be valuable as a benchmark, as many details as possible about the experiment should be recorded. Target properties of particular interest are composition, grain size, density, porosity, friction angle, and strength. Projectile energy, velocity, and angle must also be available. At a minimum, the final shape of the crater and ejecta blanket must be known. Anything that can be done to track particles during crater formation, or just recording pre- versus post-impact particle position, is of enormous benefit.

2. More systematic experimental work on material properties. This work is needed to characterize material properties in support of the increasingly sophisticated models that are being developed for impact crater collapse studies. In particular, parameters associated with material porosity and strength are not well characterized, and often values not appropriate for geological materials are used in model efforts, in lack of anything more appropriate. These experiments should be accompanied by the collection and
distribution of older work, which is often not well known by the community.

3. Detailed field studies of mid-sized, 15–30 km in diameter, terrestrial craters. It was suggested that a field research program be developed to thoroughly characterize terrestrial impact craters in the 20–30 km diameter range. There are a handful of these craters that are well-preserved and well-exposed. They occur in a variety of targets, both sedimentary and crystalline. They are large enough that they contain many of the complex structures observable in planetary craters. Each crater should be studied with an emphasis on thoroughly characterizing the amount and nature of deformation outward from the crater. Is the deformation brittle or ductile in nature? Does deformation occur over broad areas, or in small discrete zones? The locations and volumes of melt should be noted. It is also very important to attempt to evaluate how far material has moved during the impact process.

Create a Long-Term Study Project

There was consensus that the impact cratering process would be a good candidate for a long-term organized community study project. Such a study project might be envisioned as being organized and conducted in a manner similar in nature (but not magnitude) to the Basaltic Volcanism Study Project. Different teams of scientists would work to summarize the existing state of knowledge of different aspects of the cratering process, conduct short-term research to fill minor existing gaps, and put forth plans for long-term research. Teams would work under the broad direction of an organizing committee with the goal of producing a compendium state-of-knowledge for the cratering process where the whole is greater than the sum of the parts. A suggested way to divide the cratering process into manageable topics for the teams are the session topics for the workshop, with the possible addition of topics like “Cratering flux in the solar system”, and “Environmental consequences of impact.”

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