SUMMARY OF SESSION ON THERMODYNAMICS OF IMPACT CRATERING AND DETERMINING IMPACTOR CHARACTERISTICS, SATURDAY, FEBRUARY 8, 8:30 A.M.

Summary by Bevan M. French

[*] = Senior Author of paper in this session. (I) = invited paper; [ ] = Senior Author of paper in another session.

Introduction

The two topics in this session are widely separated, but they both share the workshop's common theme: the need to build bridges between theoretical studies (theory, modeling) and geological field observations. The papers and discussions provided a good start. If the necessary bridges have not yet been built, at least we now have some idea what they should be made of and where they should go.

Thermodynamic data, and information about thermodynamic processes, are critical ingredients for models of how large and small impact craters form. The same factors also control major aspects of the geology of real-world impact craters: the volumes of deformed rock, the production of impact melts, the distribution of post-shock temperatures, and post-impact hydrothermal activity within the crater. The problem is how to go back and forth between models and geological field observations in order to understand them both.

The other problem, i.e., how to determine the nature of the impactor from the characteristics of the resulting crater, has long been hampered by too little data. The impacting object is virtually destroyed during impact, and its traces generally remain only as chemical signatures in the crater rocks. Progress in this area requires not only connections between several different areas, but a great deal of new and specific information within the areas themselves.

Thermodynamics in Models and Real Impact Craters

A large number of theories, models, and computer codes already exist for studies of shock-wave phenomena and impact crater formation [e.g., *O'Keefe (I); *Ahrens]; detailed discussions were given in other sessions [Melosh (I); Holsapple (I); Housen (I)]. These resources, combined with high-speed computers, can generate impressive and increasingly realistic simulations of the larger-scale phenomena in terrestrial impact craters.

However, these theoretical approaches are hampered by problems with both the input data and the relative simplicity of the models compared to impact structures in the real world: (1) Equations of State are relatively simple and may not correspond well to natural complex (e.g., polymineralic) rocks; (2) the ability to model complex targets that consist of multiple rock types (e.g., the geologically common arrangement of layered sedimentary rocks over a crystalline basement) or that have a pre-existing deformation fabric (fractures, schistosity, etc.) is limited; (3) the treatment of changing rock properties (strength, internal friction) as a result of damage produced during impact is an area of special concern that is not well modeled, but it is crucial for understanding such problems as the development of central uplifts in large impact structures.

These presentations provided a major benefit to the geologists at the workshop: a better understanding of the assumptions, oversimplifications, strengths, and limitations of modeling studies. It was also important, while watching the impressive computer simulations in color-coordinated video, to appreciate the fact that models are not at the stage where they can provide specific predictions about the details of individual impact structures. For example, depending on the model, the calculated penetration depth for the Chicxulub structure varies between 37 and 60 km [*O'Keefe (I)]. An important question that gradually took shape during the session was: What data and modeling methods can provide the best predictions for what is actually observed in impact structures, especially at the scales (cm to km) best observed by field geologists?

At the other end of the yet-unfinished bridge, where the field geologists congregated, the question was reversed: What geological observations in real impact craters can provide critical testing and improvement of models? (Virtually all this discussion dealt with terrestrial impact structures, where small-scale data are obtainable.) The rocks of impact structures are the only preserved records of conditions during and after the impact event itself: shock-pressure levels and gradients across the structure; timing of rock movements and production of impact lithologies; and the thermal conditions during and after shock, as reflected in the production of impact melts and the development of post-impact hydrothermal activity.

Geological studies, many done back in the 1960s and 1970s, have been successful in establishing some basic principles about impact structures: (1) the qualitative understanding of crater excavation mechanisms [Herrick]; (2) the presence of higher shock pressures in the center of the structure [*Gibson (I), *Dence (I)]; (3) the decline of shock pressures away from the center by a power law which, unfortunately, appears to have different exponents in different parts of the crater [*Dence (I)]; (4) the clearly different responses between dense crystalline rocks and porous sedimentary rocks to the same shock pressures; (5) the apparently constant depth/diameter ratio (about 1/3) of the transient crater; (6) the similarly constant ratio of about 1/10 between maximum central uplift and crater diameter; (7) the measurement of post-shock temperatures and metamorphic effects involving impact melts and hydrothermal deposits.

However, in contrast to the large numbers of models and supporting data, detailed geological information is still limited and hard to obtain [*Gibson (I), *Dence (I), Spray (I), Osinski]. The major problem is not the small number of craters available for study (actually >170 are known) but the small size of the impact geology community. The number of impact geologists is probably not much larger than the number of impact craters; as a result, few craters have been studied in any detail after their original identification. (Some exciting exceptions described at the Workshop are Vredefort, South Africa [*Gibson (I)], Sudbury, Canada [*Spray (I)], Houghton, Canada [*Spray (I), Osinski], and Kärdla, Estonia [Jöeleht, Versh].) Another basic geological problem is that it is a long, hard job to study even a small impact structure in detail at the intermediate scales between field maps (km) and thin sections (mm-cm). Another problem is funding; routine, long-term field-geology studies, regardless of their value, do not appear new and glamorous to highly-strained funding agencies, and there was a murmur of agreement at a comment that it was often easier to get several hundred thousand dollars for a new analytical instrument than to get a tenth of that amount for field work.

Despite the wide separation that still exists between modeling and field geology, some directions for closing the gap became clear during the workshop. Modeling studies should try to become more realistic and more predictive, with efforts aimed at reproducing specific craters by using detailed geological descriptions of their target rocks. [The work being done on Vredefort by Gibson, Reimold, Turtle, Pierazzo and others is an exciting example of how such a focused study can be carried out.] Secondly, to the extent possible, modeling studies can try to predict rock deformation, especially fracturing and other fine-scale deformation, at scales that can be observed and compared by field studies. New and improved (and unfortunately, probably more complex) Equations of State can be constructed to reproduce better the polymineralic nature of real rocks, and more sophisticated functions can be developed to represent the behavior of damaged target rocks during the impact process.

Geologists, in mapping impact structures, need to pay more attention to medium-scale (m-cm) deformation features and the larger patterns that they form. One example is the unsatisfactory state of information about the geological details of central uplifts. Even though many craters have well-exposed and mappable central uplifts, few of them have been mapped well enough to show small-scale details. There is still uncertainty and debate about the extent to which central uplifts are fragmented and how they have moved upward. What is their preserved degree of coherence? Are they relatively strengthless bodies of rubble (the “megabreccia” of Shoemaker’s early work)? Or are they coherent rock bodies moved upwards intact like pistons? Detailed field mapping of several well-preserved structures could help settle these issues.

Another issue that appeared frequently during this session and in the Workshop itself is the nature of deformation in the subcrater rocks immediately below the crater floor. How are these rocks deformed during the impact? Can they really be driven rapidly downward, perhaps for distances of kilometers, during formation of the transient crater, then equally rapidly restored almost coherently to form the central uplift? How does this happen geologically? Geologists need to map in detail the few craters in which both the crater floor and the shallow subcrater rocks are exposed. A related problem is the fact that shock pressures and shock gradients have been measured in only a few impact structures [*Dence (I)]; more extensive studies would provide modelers with important information about the state and distribution of at least one key thermodynamic variable, shock pressure, during crater formation.

Thermodynamics in Thermal Impact Processes

Several papers in the session addressed thermodynamic processes that occur both before and after the crater itself has formed: the nature of vaporization during the impact, and the formation of hydrothermal systems and possible ore deposits after the crater itself has formed.

Vaporization is critical to modeling the earliest stages of the impact process, during which the projectile and much of the target are consumed, large amounts of vapor are ejected upwards, and near-surface target material is ejected at high velocities to form distal ejecta, spherule deposits, and possibly tektites. At the same time, realistic representation of vapor in computer models is difficult because the physical processes and the thermodynamic properties are largely unknown. Two papers described experimental attempts to provide better information: measurement of actual parameters in an impact-produced vapor plume [*Sugita], and chemical studies of the actual species produced by vapor condensation [*Gerasimov]. These two studies showed how complex the subject is and how much more there is to be done. Sugita's experiments demonstrate the possibility of actually measuring critical vapor parameters that previously had to be assumed in calculations. Gerasimov's studies showed that silicate vaporization is complex, and the most dominant species in superheated vapors may be atomic clusters rather than the more computer-friendly single atoms.

The problem of post-shock temperatures in impact structures is becoming more important with the realization that long-lasting impact-produced heat can mobilize nearby water, form hydrothermal systems and ore deposits, and perhaps contribute to the origin and development of life. Traditional methods of mineralogy and petrology, applied to the rocks of impact craters, have been remarkably successful in estimating post-impact temperatures from mineral assemblages [*Gibson (I)] and in using mineral inclusions to determine temperatures and fluid compositions of hydrothermal systems in impact structures [*Jõeleht]. These data can then be used as tests of computer models to compare predicted and measured temperatures for the same crater. These studies have important implications for craters on other planets, especially Mars, where impact-produced hydrothermal systems may play an important role in melting permafrost and moving liquid water around [*Newsom].

Estimating Impactor Composition from Craters

Most of the effort in this field has involved geochemical analyses, trying to establish the presence of extraterrestrial projectile material in the crater rocks, and then trying to match the estimated composition of the projectile with the compositions of known meteorite types. This research area [*Koeberl (I)] has expanded greatly in capability and complexity since the simple measurements of excess Ir by the Alvarez group in distal ejecta from the Chicxulub crater established that a major meteorite impact had occurred at the end of the Cretaceous. Subsequent research has also been based on the analysis of impact crater materials, but there have been numerous new developments: (1) the use of newer, more sensitive, and more sophisticated analytical methods; (2) extensive measurements of siderophile element ratios and their comparison with known meteorites; (3) use of isotopic systems of several elements (Os, Cr, and W) to identify low amounts of extraterrestrial components and to distinguish between meteorite types.

There are now several accepted geochemical indicators for an extraterrestrial signature in impact craters, but it has been harder to relate the observed signatures to a specific type of projectile, and the appearance of better analytical methods has been balanced by the recognition of new problems. Detection of small amounts of extraterrestrial material in impact melts is complicated by the difficulty in correcting for amounts of the same siderophile elements in the indigenous target rocks. Even when larger amounts of projectile material are present, its amount and distribution in impact melts and other rocks from impact craters is not uniform; in fact, it can vary widely (from undetectable to several percent) between nearby samples. More puzzling is the fact that, at two craters (Meteor Crater, Arizona; Wabar, Arabia), small bodies of impact glass have siderophile element ratios that do not match the known composition of the preserved iron meteorites that formed the craters. There are additional problems in using elemental ratios that actually result from secondary alteration and differential redistribution during post-impact hydrothermal activity, metamorphism, and weathering.

Even with accurate and reliable analyses, there are further problems at the other end, in trying to connect the data with a specific meteorite type [*Koeberl (I)]. Many meteorite groups are not well-characterized by modern chemical analyses, and even meteorites with good analyses may show wide ranges in the contents of key elements. Nor is there any guarantee that the compositional groups of present meteorites correspond to the populations of objects that fell to Earth tens or hundreds of millions of years ago. Finally, the critical problem of distinguishing between cometary and asteroidal impactors is blocked by the lack of data on comets and the need to use data from Interplanetary Dust Particles (IDPs) as proxies.

With the problems, however, have come ideas for studies to solve them: (1) more detailed and systematic studies (and restudies) of chemical signatures, especially in craters for which the nature of the impactor is independently known; (2) better understanding, through both analyses and modelling, of how projectile material is actually distributed into impact crater rocks; (3) more studies of how different projectile elements separate under impact and post-impact conditions; (4) better understanding of elemental behavior during vaporization, which is the process that actually transfers most (if not all) of the material from the projectile to the impact-crater rocks.

An alternative approach to determining other impactor characteristics (e.g., size, density, impact velocity) is to apply scaling laws to deduce them from measured crater parameters (e.g., diameter, impact melt volume) [Holsapple]. Although the paper concludes that the prospects are not encouraging — the various scaling laws are too close in nature to yield precise estimates — the idea should be followed up, because it provides the hope of determining projectile characteristics that cannot easily be established by chemical means. In the meantime, it seems wise to be a little skeptical about precise matches between projectiles and their craters, and even more skeptical about the more basic distinction between cometary and asteroidal impactors.

Conclusions

The papers and discussions in this session and elsewhere in the workshop provided a good start to bridging the gaps between the "modelers" and "geologists." They provided useful contacts between the two groups and the individuals in them. Each group ended up more aware of the other's work; more important, there was a better understanding of the problems, assumptions, simplifications, weaknesses, and individuals involved in each type of research. There was an encouraging amount of spontaneous discussion of future workshops and future research projects, and everybody went away with new ideas about how to make their future studies more realistic and more valuable to the others. There were plenty of good ideas reported, generated, and talked about. Now the challenge is how to find the people and resources (both time and money) needed to get them moving.