

**EPIC FAILURE: A STUDY OF SUBSURFACE DAMAGE FOLLOWING
OBLIQUE HYPERVELOCITY IMPACTS**

BY: ANGELA M. STICKLE
B.S., UNIVERSITY OF WASHINGTON, 2007
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This dissertation by Angela M. Stickle is accepted in its present form by the Department of Geological Sciences as satisfying the dissertation requirement for the degree of Doctor of Philosophy.

Date

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CURRICULUM VITAE

Angela Marie Stickle

Date of birth: August 6, 1984

Place of birth: Bremerton, WA, USA

Education

- | | |
|-----------|--|
| May 2012 | Brown University, Providence RI
Ph.D in Geological Sciences
Concentration: Planetary Impact Processes
Advisor: Peter Schultz |
| May 2011 | Brown University, Providence RI
Master of Science in Engineering
Concentration: Solid Mechanics |
| May 2009 | Brown University, Providence RI
Master of Science in Geological Sciences
Concentration: Impact Processes
Advisor: Peter Schultz |
| June 2007 | University of Washington, Seattle WA
Bachelor of Science in Aeronautical & Astronautical Engineering
Bachelor of Science in Earth and Space Sciences (Physics), with distinction |
| June 2002 | North Kitsap High School, Poulsbo WA
High School Diploma, with honors. Graduated 9 th of 420 students. |

Research Experience

September 2007-present Research Assistant, Brown University, Providence RI

- Advisor: Peter Schultz
- Designing and performing impact experiments at the NASA Ames Vertical Gun Range focusing on the evolution of damage and failure mechanisms following oblique impacts.
- Analyzing 3D hydrocode models of hypervelocity impacts, using the CTH hydrocode from Sandia National Labs, to compare with laboratory experiments and further the understanding of processes at large scales.
- Presented at national and international conferences

Autumn 2003 - June 2007 Student Researcher, UW Space Physics Research Group

- Advisors: Robert Winglee and Erika Harnett
- Analyzing 3D multifluid computer models of the magnetospheres of the Earth, Mars, Saturn and Jupiter. Computer programs learned and used: Data Explorer, Adobe Suite, MATLAB. Computer models were written in FORTRAN.

- On the MagBeam propulsion project, responsibilities included: helping to collect plasma and magnetic field data using Langmuir and B-dot probes, and helping to construct and test various hardware pieces for the experiment.

June - August 2006 Summer Intern, Jet Propulsion Laboratory, Pasadena, CA

- Space Grant summer intern in the Reliability Engineering Office.
- Responsibilities included: helping to create, run and analyze computer models of the Jovian aurora in order to conduct a charging analysis for the JUNO mission.

January 2006-2007 Student Researcher, UW Aeronautical/Astronautical Engineering Dept.

- Student researcher on the Ionic Wind lifter project
- Duties included: Design and construction of new lifter bodies, and testing for characteristics.

Honors and Awards

- Grant, Bevan and Mary-Hill French Fund for Meteorite Impact Studies, 2012
- Brown University Dissertation Fellowship, Sept. 2011-January 2012
- Outstanding Student Paper Award in the Union Section at the 2010 AGU Fall Meeting
- Elected to the Brown University chapter of Sigma Xi honor society, 2011
- NASA Rhode Island Space Grant Consortium Graduate Fellow, summer 2008, 2010-2011
- Alex Charters Student Scholar award recipient at the 2010 Hypervelocity Impact Symposium
- Nominated as one of the 10 best papers at the 2010 Hypervelocity Impact Symposium
- Elected to Sigma Gamma Tau honor society, University of Washington, 2007
- 2007 Senior Capstone Space Design Award for outstanding achievement
- Astronaut Scholarship Foundation: Astronaut Scholarship, 2005-2006

Teaching Experience

Summer 2009 and 2010 Instructor for *Exploring the Planets*, Brown University, Providence RI

- Taught week long summer course for high school students
- Designed curriculum and lesson plans, coordinated guest speakers and led daily 3-hour classes.

Spring 2010 Teaching Assistant, Brown University, Providence RI

- Teaching Assistant for *Geology 81: Planetary Geology*

- Attended lectures and discussion sections. Assisted in in-class demonstrations and assisted students during class and upon request.

Fall 2008 Teaching Assistant, Brown University, Providence RI

- Teaching Assistant for *Geology 22: Physical Processes in Geology*
- Led laboratory sections (4 sections, ~25 students a piece), held office hours upon request and graded laboratory and homework assignments.

Summer 2008 RI Space Grant Fellow, Brown University, Providence RI

- Co-taught week long summer course for high school students entitled: *Exploring the Planets*
- Designed curriculum and lesson plans

Spring 2008 Teaching Assistant, Brown University, Providence RI

- Teaching Assistant for *Geology 10: Face of the Earth*
- Led laboratory sections (4 sections, 30 students a piece), held weekly office hours and graded laboratory and homework assignments.

Spring 2007 Undergraduate Teaching Assistant, University of Washington, Seattle WA

- Undergraduate Teaching Assistant for *ESS 205: Access to Space*
- Helped lead laboratories (2 sections, ~30 students apiece), as well as field trip.
- Helped students design/build experimental payloads for final project.

Teaching-related activities

Rhode Island Space Grant Fellow

- Planned and delivered 1-2 hour lessons about basic geological processes, introductory lessons about planetary geoscience, the Moon, Mars and impact cratering to students in grades 1-12. Lessons included lectures, demos and small-scale laboratory experiments.
- Co-wrote the RI state exam for the 2011 National Science Olympiad

Science lessons at Vartan Gregorian Elementary School, Providence RI

- Planned and delivered ~1 hour long geology and basic science lessons for second graders at Vartan Gregorian Elementary. Lesson topics included: Sedimentary layers and depositional environments, grain size and sorting, flooding and the Nile river, forces and basic planetary geology. Further lessons on the properties of air included: Properties of matter, the scientific method, aerodynamics.

AIAA outreach events, Seattle WA

- Planned and delivered lesson on basic aerodynamic forces on airplanes and rockets in the atmosphere; including Newton's laws, and the concepts of Lift/Drag/Thrust
- Taught lessons on water-rocket building, and supervised building and testing of water rockets

Professional Memberships

American Geophysical Union, since 2004

American Institute of Aeronautics and Astronautics, since 2005

Society of Women Engineers, since 2006

Association of Environmental and Engineering Geologists, since 2010

Society of Experimental Mechanics, since 2011

Publications

Peer Reviewed papers:

Stickle, A.M., P.H. Schultz (2011), Exploring the role of shear in oblique impacts: A comparison of experimental and numerical results for planar targets, *International Journal of Impact Engineering*, 38, 527-534, doi:10.1016/j.ijimpeng.2010.10.025

Harnett, E. M., R.M. Winglee, **A. Stickle**, and G. Lu (2008), Prompt Ionospheric/Magnetospheric Responses Oct. 29, 2003 Halloween storm: Outflow and Energization, *Journal of Geophysical Research*, **113**, A06209, doi:10.1029/2007JA012810

Winglee, R.M., E.M Harnett, **A. Stickle** and J. Porter (2008), Multiscale/multifluid simulations of flux ropes at the magnetopause within a global magnetospheric model, *Journal of Geophysical Research*, **113**, A02209, doi: 10.1029/2007JA012653

Winglee, R.M., W.K. Peterson, A.W. Yau, E. Harnett, **A. Stickle** (2008), Model/data comparisons of ionospheric outflow as a function of invariant latitude and magnetic local time. *Journal of Geophysical Research*, **113**, A06220, doi: 10.1029/2007JA012817

Stickle, A.M., P.H. Schultz (2012) Subsurface damage from oblique impacts into low-impedance layers, (submitted to JGR-P, in review)

Stickle, A.M., P.H. Schultz (2012), Investigating Pressure Magnitudes at Depth for Oblique Impacts into Layered Targets: Applications to Impacts into Sedimentary Targets (in preparation)

Stickle, A.M., P.H. Schultz (2012), Discrete shear failure planes resulting from oblique hypervelocity impacts, (in preparation)

Conference Abstracts

Stickle, A.M., P.H. Schultz (2012), Subsurface Damage Features Following Projectile Decapitation, *LPSC 2012*, Abstract #1269. (poster)

Stickle, A.M., *et al.* (2012), Vulcan: A Concept Study For A New Frontiers-Class Venus Lander, *LPSC 2012*, Abstract #1939. (poster)

Stickle, A.M., P.H. Schultz (2011), Investigating Pressure Magnitudes at Depth for Oblique Impacts into Layered Targets: Applications to Impacts into Sedimentary Targets, presented at the Annual Meeting of the Meteoritical Society in Greenwich, England, August 8-12, Abstract #5482. (talk)

Stickle, A.M., P.H. Schultz (2011), Substrate Effects from Oblique Hypervelocity Impacts into Layered Targets, *LPSC 2011*, Abstract #2698. (poster)

Schultz, P.H., **A.M. Stickle** (2011), Arrowhead Craters and Tomahawk Basins: Signatures of Oblique Impacts at Large Scales, *LPSC 2011*, Abstract #2611.

- Stickle, A.M.,** P.H. Schultz (2010), Effects of Impact Angle and Target Structure on Seismic Efficiency, Abstract U51B-0043 presented at the 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec. (poster)
- Stickle, A.M.,** P.H. Schultz (2010), Exploring the role of shear in oblique impacts: A comparison of experimental and numerical results for planar targets, presented at the 2010 Hypervelocity Impact Symposium in Freiburg, Germany, April 11-15. (talk)
- Stickle, A.M.,** P.H. Schultz (2010), Comparing Experimental and Numerical Results for Subsurface Failure Following Oblique Impacts into Planar Targets, *LPSC 2010*, Abstract #2598. (talk)
- Stickle, A.M.,** P.H. Schultz (2009), Oblique Impacts into Low Impedance Layers, *Eos*, Vol. 90, Number 52, 29 December 2009, Fall Meet. Suppl., Abstract PP31D-1384. (poster)
- Schultz, P.H., **A.M. Stickle** (2009) Lost Impacts, *Eos*, Vol. 90, Number 52, 29 December 2009, Fall Meet. Suppl., Abstract PP33B-04.
- Stickle, A.,** Schultz, P.H. and D.A. Crawford (2009), The Role of Shear in Oblique Impacts, *LPSC 2009*, Abstract #2357. (poster)
- Stickle, A.,** Winglee, R.M., Snowden, D., Kidder, A. and E. Harnett (2006), Simulations of the Coupled Interaction of the Titan's Induced Magnetosphere with Saturn's Magnetosphere, *Eos Trans. AGU*, 87(52), Fall Meet. Suppl., Abstract SM23A-0281. (poster)
- Stickle, A.,** Winglee R.M., and E. Harnett (2005), Relationship Between Substorm Onset and Reconnection in The Magnetotail,, *Eos Trans. AGU*, 86(52), Fall Meet. Suppl., Abstract SM31A-0389. (poster)
- Stickle, A.,** Winglee R.M., Harnett, E. and C. Paty (2004), Plasma sources and lifetimes within the Jovian magnetosphere, *Eos Trans. AGU*, 85(47), Fall Meet. Suppl., Abstract SM33A-1251. (poster)

Talks and Public Outreach

- 4/19/11: "Studying impact craters on planetary surfaces: how and why?", presentation for the Brown University Ambassador program
- 4/9/11: "Effects of Oblique Hypervelocity Impacts into Layered Targets", presented at the RI Space Grant Research Symposium April 8, 2011
- 5/07: "Luna POLARIS: A Lunar Positioning and Communications System", presented at the USRA RASC-AL (Revolutionary Aerospace Systems Concepts-Academic Linkage) workshop in Galveston, TX
- 8/06: "Plasma sources and lifetimes in the Jovian Magnetosphere", invited talk at CalTech, Jet Propulsion Laboratory
- 8/06 "Auroral Charging in the Jovian System", noontime seminar at the Jet Propulsion Laboratory

Activities and Skills

Computer skills: Proficient in the Adobe Creative Suite (incl. Photoshop, InDesign, Illustrator), MS Word, MS Excel, MS Powerpoint, MATLAB, Mathematica and ImageJ, SolidWorks and ANSYS. Programming in FORTRAN, MATLAB and related languages. Comfortable with UNIX, Windows or Max OS. Familiar with ENVI and ABAQUS.

Experimental Experience: Designed and performed multiple experiment runs at the NASA AVGR; includes designing experiments, creating targets, and using high-speed imaging for data analysis.

Language: Conversationally proficient (written and spoken) in German and Spanish.

University Activities: Geology representative to the Brown Graduate Student Council (2009-2011); Graduate student Faculty representative (2011-2012); Member of Greek folk dancing and singing groups.

Other Activities: Attended the ExxonMobil Geoscience Field Course in the Guadalupe Mountains (March 2012); Attended the 23rd JPL Planetary Science Summer School (Team VULCAN, July 2011) to design a concept study for a Venus lander, student Mechanical/Configuration lead; Structure and Mechanical Lead for the Student Capstone Design Project *Luna POLARIS* (A Lunar GPS system), University of Washington 2007

ACKNOWLEDGEMENTS

Getting through graduate school successfully is not a lone endeavor. It seems inadequate to just list names of those who have helped me through this experience. However, those who have ever written a thesis may know that sometimes words are inadequate (or failing around turn-in time) and so a list is what may happen. Nevertheless, the people named below have encouraged me, supported me, and helped me immensely on my journey to grad school and through these past five years.

My road to Brown was not extraordinarily circuitous, but it wasn't a straight shot either. Like many children, I wanted to be an astronaut when I grew up. I was obsessed with all things NASA and space, and *knew* I would someday work for NASA. My plan was to become a brilliant rocket scientist and go to the moon. It seemed so straightforward. So, I enrolled at the University of Washington with plans to major in Aeronautical/Astronautical engineering and to continue on into private industry building satellites or rockets before eventually landing a dream job at NASA. Part of this became a reality. I did major in Aero/Astro (fondly known as "AA" to those of us in it), but my plan to work in private industry took a turn during my sophomore year of college, because that was when I met Robert Winglee, and when I decided to double degree in Earth and Space Sciences.

During the beginning of my sophomore year of college, I told the undergraduate advisor for geology that I was "interested in space" and that I wanted to do research somewhere on campus. He suggested I contact Robert. I did, and the trajectory of my studies (and my eventual graduate school v. job decision) shifted completely. I learned so much from Robert, and I was given many wonderful opportunities for research,

presenting at conferences, and summer internships. I'll always remember my first AGU, and Robert coming to my rescue when I shot him a panicked look across the poster hall as I was accosted by big, scary, famous scientists. When he suggested that I minor in physics, because "really, you only need two more classes", it made all the sense in the world. His passion for science is infectious, and even though we fondly referred to him as a "little ball of chaos", working in his lab taught me to do thoughtful and careful research.

Thus, to Robert, and to my other undergraduate research advisors, thank you. Without the guidance and support you gave me, I might never have gone to graduate school. Erika Harnett and Carol Paty, you gave me support and taught me so much beyond doing good research. Dr. Garrett, my summer at JPL was amazing, and your advice was invaluable when I was choosing a graduate school.

Everyone I talked to told me to apply to Brown, and I did because the program was good and the faculty were doing interesting research. And so, when I was a young, eager, senior in college, I visited the Geological Sciences department. It was a whirlwind couple of days of east coast graduate school visits, and to be honest what I remember most is being thoroughly exhausted. But the professors were eager and excited about their research, and the graduate students were amazing. Beyond that, what I most remember is having lunch with the graduate students in LF 105. What a loud, chatty, friendly group of people! Noah Petro told me about his terrifying prelims experience, and to this day I believe that was why I was so scared of them. I also firmly believe what I was told then, and what I have since told every prospective student that I have seen come through Brown: "Brown Geology is a *great* place to be a graduate student, because

the other students are amazing.” This is beyond true. The graduate student community within the Brown Geology department is a tight knit group of remarkable people who are curious, smart, adventurous, and willing and eager work hard and to have a good time. Beyond the late nights and hard work, students really define the graduate school experience. So, without further ado:

To the students who went before me: Thanks for your advice, your help (in school and out), and your example. We all strive to be as cool-headed, confident, successful, and just so damn cool as all of you. A few people deserve special mention. Carolyn Ernst, thanks for introducing me to Brown and Providence, explaining the ropes, and for your continued support and advice. Rachel and Allan Klima, you are amazing. Thanks for the fun times, the craft nights, and wacky lunchtime stories. Rachel, your advice was always invaluable. Joe Levy, thanks for the home brew and adventures in RI. Peter Isaacson, and Kate Burgess, thanks for introducing me to RIPUL and a love of IPAs. Linda Chernak Meyers, thanks for keep me abreast of the happenings in geo! Bethany Ehlmann, what can I say? We’ve had some adventures, let’s have more! Sam Schon, you are a delightful person. Thanks for the rides to PA, the hospitality, and the friendship. Ailish Kress, thanks for the fun, and for introducing me to the Greeks (who all deserve their own very special hugs)! Stavroula Chrysanthopoulou, thanks for teaching me to dance. Grad school wouldn’t have been the same without you.

To my cohort, we didn’t do too badly, huh? Li Gao, Susie Theroux and McCall Bureau: I didn’t see you geochemers as much as I would have liked, but thanks for the good times! Brendan Hermalyn, somehow we survived the great adventure, craziness and all. Lillian Ostrach, thanks for introducing me to Providence and for being an

awesome friend and motivation from afar. Ulyana Horodyskyj, what can I say roomie? You're awesome, thanks for always being there, and for taking me along on all your wacky adventures. Debra Hurwitz, we had some crazy times our first couple years, and your friendship means a lot to me. To you and J.R. Skok, thanks for being fantastic thesis-buddies. J.R., I am glad to be your friend, and thanks for the adventures! Among my incoming class, there is one that deserves an extra-special shoutout: Heather Ford, your friendship is priceless. I am grateful for your companionship, support and advice during these past five years.

To the students still making their way through, best of luck! Trust me, *somehow* you will finish. Don't let anyone ever tell you it is easy, but it can be done. While I could probably list every student who has been at Brown during my time in some way, that would be exhausting for me and, more importantly, for anyone who might be reading this. So, suffice it to say that I have enjoyed getting to know you all. Special acknowledgements go out to: Kerri Donaldson-Hanna, Kat Scanlon, Rebecca Greenberger, David Hollibaugh-Baker, Janette Wilson, Jenny Whitten (keep on dancing!), Jess!! Rodysill, Shannon Loomis, Jeff "old man" Salacup, Colin Jackson, Hillary O'Brien, Michael Beach, Marky-Sparks Salvatore, Rocio Gill, Amanda Getsinger, Mary Peterson, Megan Bruck Syal, Sam Bell, Stephanie Quintana, and Tim Goudge, thanks for all the good times. LeAnne Edwards and Leah Cheek: I will always cherish our LF 305 date nights. Leah, a special thanks and virtual huggles goes to you for sticking by me for four years, and for dealing with my constant "thesis-updates" with grace and smiles. All of you helped keep me sane during this crazy journey, and it's been great. Let's keep having Brown reunions at conferences!

I would be remiss if I did not also thank my “engineering kids”: Jennet Toyjanova, Eyal Bar-Kochba, Michael Chon, John DiBenedetto, Gerard Leyson, Greg Rizza, Liz Doyel, Sean Teller, and Rye Waldman, thanks for providing so much fun away from work and geology. I also have to include my utterly amazing engineering math study group: Andy Stone, Brandon Arteaga, Ward Weathers (and all those who joined later), I couldn’t have done the masters without you for I definitely would have failed math... “And we’re done!”

And to my AA-kids, especially Greg Quetin and “Kimbarlee” Shish, your support and friendship from the left-hand-coast have been unflagging. Greg, thanks for being a Jerk, with a capital J (but in a good way), and Kim, we suffered through this graduate school thing together—now it’s your turn to finish! It’s been rough and tumble, but most great journeys are.

Words fail me entirely when I try to thank Laura Kerber and Bronwen Konecky, who both deserve very special acknowledgement. Without their unfailing friendship, advice, craziness, support, and willingness for adventure, I would not have made it through these past five years. I love you girls.

I have been privileged to learn from many amazing people during my time here at Brown. First, I would like to acknowledge several members of the Engineering faculty: Professor Freund, thank you for teaching me continuum mechanics, and for being concerned when I made silly mistakes. Also, thanks for the math final: it was a doozy, but your apology afterwards was very sweet. Professor Dorca, thanks for teaching me complex analysis so very thoroughly! To Professor Bower, who asked me “What are you doing here?” when I showed up to his classes without registering for them. My answer,

as always: “To soak up more of your wisdom.” Professor Kenny Breuer, you taught me that looking up original G.I Taylor papers will always lead to good things. And to Professors Blume and Kim, who were my engineering advisors for my Masters degree, thank you.

Second, I turn my attention to the amazing faculty in the Geology department. I have learned so much from them. I would especially like to thank the members of my advisory committee: Greg Hirth and Karen Fischer, who were so supportive throughout my time here, and always willing to talk about research or grad school or life. Greg also introduced me to rheology, which helped shape my graduate studies. Amy Barr, who opened up her office for all manner of chats over the past year. Don Forsyth and Marc Parmentier, who really taught me to love geophysics. A special shoutout goes to Marc for drawing graphs for me during prelims. Mike Wyatt introduced me to science on Mars, and encouraged me to talk in class. And Carle Pieters, who taught me my first planetary science course, which was a spectacular introduction to remote sensing. She made sense of squiggly lines, and her love of the moon was contagious.

The Geology department is blessed with a truly amazing support staff. Thanks to Lucia Tavares for her bright smile and for keeping my office plants alive, to Celeste Thompson-Roach, Nancy Christie, Anne Cote, Jess Muirhead, and Margaret Doll for always being there to answer questions and help with paperwork. Bill Collins was especially helpful and friendly during my entire tenure at Brown. And a special thanks to Juliet Duyster for all things Space Grant.

I turn my attention now to my advisor, Pete Schultz, who deserves a great many thanks for shepherding me through the past five years with patience. Pete has a brain full

of ideas, thoughts and interesting science questions to solve, and through him I have learned to embrace (and love) the world of impact cratering, even if it sometimes drives me crazy. His love of cratering and enthusiasm for planetary science is infectious. Pete taught me a great many useful things, not least among them how to perform experiments at the AVGR, and how to properly clean windows. He also taught me to look at many sides of a problem before diving into the details (even if I didn't always follow that advice), and how to go about answering science questions thoughtfully and thoroughly, and, of course, with proper grammar! Isaac Asimov said: "The true scientist is quite imaginative as well as rational, and sometimes leaps to solutions where reason can follow only slowly." Pete, you are a true scientist, thank you for teaching me it's OK to use my imagination and leap sometimes, so long as rational, logical experiments follow behind.

Being a "Pete Student" has certain advantages (who else gets to say they shoot "NASA's really big gun" for a living?), not least of which is the wonderful "Pete family" you become a part of (Pete family dinners are always a good time!). I am forever grateful to Dave Crawford, one of the best "big brothers" a grad student could ask for. Thank you for all the CTH help, and for answering all of my questions and concerns patiently, honestly, and kindly. You really have been amazing. To other former Pete students, especially Olivier Barnouin, Carolyn van der Bogert, and Jenn Anderson, it's been wonderful being a part of the group—thanks for the support! A very special thanks goes out to the guys at the Ames Vertical Gun Range. Big Don, Rick, Little Don and JP, we couldn't have done this without you. Thanks for the good times.

Thanks, too, to my Ph.D committee: Amy Barr, Karen Fischer, Greg Hirth, and John Spray. Their comments and support made this a stronger thesis.

Lastly, I would like to use this opportunity to thank my family, who have been more supportive than anyone could ever ask for. My parents always told me that I could be anything I wanted to be, and more. Thank you for your unflagging support, love, advice, and help throughout the years. Mom, I miss you every day. Daddy, you are amazing. Thank you for being so understanding and supportive of my choices, even when it meant moving across the country. It was your strength that helped me grow into the person I am today, and to never give up (especially when things got hard)!

To my brothers, Nick and Alex. You've been a pain in the neck my entire life, but I love you anyway. You always believed in me, even when I didn't believe in myself, and I'm grateful for that. You have my back and I will always have yours. But now, you'll have to call me Doctor Angela!

I end this with a quote from one of my favorite books: *The Voyage of the Basset* by James C. Christensen, which I feel is an appropriate way to sum up this whole crazy experience, and also to begin a scientific dissertation:

“Imagination is where science begins!” the professor explained, thumping his stick. “Not with charts and tools and measurements. First the idea, *then* the experiment!”

Thank you everyone for teaching me to use, and embrace, my imagination.

PREFACE

Impact cratering is a ubiquitous process affecting planetary surfaces in the solar system. On Earth, impact craters can be economically useful, providing reservoirs of nickel and copper ores [e.g., Dressler et al., 1987] or drilled for hydrocarbon reservoirs [e.g., Grieve and Masaitis, 1994; Curtiss et al., 1998]. In planetary science, impact craters represent one of the dominant processes in the surface evolution of planets, as well as a window into the subsurface through orbital remote sensing. Two very successful, recent, cratering experiments exploited this aspect of cratering: kinetic probes excavating below the surface of a comet (Deep Impact, [e.g., A'Hearn *et al.*, 2005]) and the Moon (LCROSS, [e.g., Colaprete *et al.* 2008; Schultz *et al.*, 2010]). Despite their importance in solar system evolution, however, many questions still remain about the formation of impact craters. One such question involves damage structures seen in oblique impacts: namely, what deformation modes are responsible for their formation?

The work in this dissertation demonstrates a unique way to approach the study of damage following oblique hypervelocity impacts. Namely, we use impact angle, impact velocity and projectile type to vary conditions within experiments that then allow exploring similar processes at much larger scales. This variation is done both in laboratory experiments and numerical models which provides new insights into geologic observations made at the surfaces of terrestrial planets.

Specific deformation mechanisms and damage structures caused by oblique impacts are studied using field observations [e.g., Kenkmann, 2002, 2003; Kumar, 2005; Poelchau and Kenkmann, 2008; Kenkmann and Poelchau, 2009], experimental work [e.g., Schultz and Anderson, 2006; Stickle and Schultz, 2011a, 2011b] and numerical

models [e.g., Collins *et al.*, 2004; Senft and Stewart 2007, 2009]. Early work on target damage focused on tensile failure following shock waves [e.g., Ahrens and Rubin, 1993; Benz and Asphaug, 1995; Melosh, 1989; Polanksey and Ahrens, 1990]. Following impact, the target material undergoes extreme compression as the shock wave expands, which is followed by rapid extension, and thus tensile failure and hoop stresses are thought to dominate beneath the impact point [e.g., Polanksey and Ahrens, 1990].

Tensile failure, though, does not capture the complete range of damage following an impact. Laboratory and numerical studies reveal that shear processes also must play an important role in subsurface failure [Schultz, 1996; Kenkmann *et al.*, 2000; Langenhorst *et al.*, 2002; van der Bogert *et al.* 2003; Collins *et al.*, 2004; Senft and Stewart, 2009; Stickle and Schultz, 2011]. Experiments show that melt is often produced by frictional processes in impacts rather than by shock heating processes [e.g., Kenkmann *et al.*, 2000; Langenhorst *et al.*, 2002], especially in geologic materials that have impurities and pre-existing structures [e.g., Kenkmann *et al.*, 2000; Barnouin-Jha *et al.*, 2005, 2007], at low impact angles [e.g., Schultz *et al.*, 2006], or at low shock pressures [van der Bogert *et al.*, 2003]. Further, shear stresses are set up behind shock waves, especially at low shock pressure, high strain-rate conditions [e.g., van der Bogert, *et al.*, 1998, 2003]. Thus, a complete understanding of subsurface deformation necessarily includes an understanding of damage resulting from shear failure.

Fully understanding damage following oblique hypervelocity impacts, then, requires answering several questions, including: what is the dominant mode of deformation, and when and where does it occur? What types of damage structures are expected to form, and what is responsible for their formation, both in laboratory experiments and on

planetary surfaces? What variables affect damage formation? Specifically, are there projectile effects? And if so, can they be identified? In order to address these questions, it is necessary to first identify diagnostic markers of failure mode in the laboratory experiments, and second to compare these to larger scale impacts on planetary surfaces. Specific damage structures within the cratering record can also reveal processes following an impact and provide context for specific processes occurring in laboratory experiments.

This thesis presents a study of damage following oblique hypervelocity impacts using a combination of laboratory experiments and numerical models. Assuming an isotropic flux, the most probable impact angle is 45° , and $\frac{1}{4}$ of all impacts in the solar system occur at impact angles less than 30° [Gilbert, 1893; Shoemaker, 1962]. Thus, a thorough understanding of oblique impacts, and the effect of impact angle on resultant damage structures and deformation mode, is necessary to truly understand the formation of impact craters on planetary surfaces.

Laboratory experiments reveal important details about subsurface damage morphology. Impact parameters (angle, velocity, projectile type) are easily changed, which can thus provide insight into controlling processes. Damage evolution in transparent polymethylmethacrylate (PMMA) targets is tracked using high-speed cameras (up to 1 million frames per second). Two different camera angles provide complimentary views of the damage growth (Figure 1): from the side, which tracks damage growth along the trajectory, and looking from uprange to downrange, which provides a view of damage growth perpendicular to the impact trajectory. Combined with insight gained from these

experiments, numerical models provide an understanding of the underlying processes responsible for specific structures and morphologies in the subsurface.

Numerical models, then, allow studying the dynamics of the impact process at all scales, and they can be used to connect laboratory experiments to geologic and remote sensing observations. Further, numerical models allow researchers to track dependent variables (e.g., temperature, pressure, density, deviatoric stress, strain, etc) with high temporal and spatial resolution when the precise impact conditions are known. In a way, numerical models represent the best-instrumented cratering experiment.

There are several caveats that must be considered when using numerical models, however. High-resolution models require significant computing resources to run, which can be prohibitive at large scales. Therefore, simulations are often run in two-dimensional space to save computing resources [e.g., Benz and Asphaug, 1995; Ivanov *et al.*, 1997; Collins *et al.*, 2004; Goldin *et al.*, 2006; Senft and Stewart, 2007]. Oblique impacts, however, require three-dimensional simulations. This requirement limits the number of cases that are run, and the resolution at which the models can be run. Further, accurately modeling deformation and failure requires sophisticated and detailed material models, which may not always be available. Thus, experimental results combined with numerical models provide one of the most important means for understanding the complex processes occurring following hypervelocity impacts.

The combination of laboratory experiments and numerical models is a general theme throughout this dissertation. Direct comparisons between laboratory experiments and 3D CTH models provide insight into the impact process and illuminate underlying physical processes that may be difficult, or complicated, to measure from experiments. The

comparisons also reveal which processes and structures are well-matched between the experiments and models at a small-scale, which better enables extrapolation to large scales. Large-scale simulations then provide critical insight into the cratering process, the mode of failure, and the ways in which this failure is manifested at large scales to explain structures seen on planetary bodies.

Chapter 1 examines the importance of shear processes in subsurface damage evolution in experiments, which is revealed by matching numerical models. This paper represents an expanded Masters thesis, detailing a suite of experiments performed at the NASA Ames Vertical Gun Range (AVGR) into planar PMMA targets. A parameter study using the CTH hydrocode from Sandia National Laboratories [McGlaun *et al.*, 1990] provides information about failure criteria for the PMMA targets, as well as discrepancies between laboratory and numerical experiments. This study shows that subsurface damage regions grow rapidly with respect to acoustic velocities of the target material, likely indicative of shear failure. Matching CTH models confirm this inference.

Chapter 2 continues with a detailed examination of damage formation in planar targets with a focus on a specific subsurface morphology. Enigmatic, sub-parallel, along-trajectory failure planes are seen in the experiments for very oblique impacts ($\theta \leq 30^\circ$), which we term “blades”. The formation of these blades is affected by impact angle, projectile type, and target geometry. Combining insight garnered from direct comparisons with CTH models, and from textural analysis of the failure planes, we show that they are likely the result of frictional processes during shear deformation following oblique impacts into the target. Further, because they form early in the cratering process

and parallel the impact trajectory, these blades are signatures of the projectile's momentum being transferred into the target.

Field observations in terrestrial craters show that pseudotachylytes, a lithology defined as a frictional melt [e.g., Shand 1916; Reimold, 1995], are found within central peaks of some terrestrial craters. Analysis reveals that two types of pseudotachylytes are found within impact craters: E-type (which form during the modification stage of impact cratering due to wall collapse), and S-type (which likely form during the early stages of impact cratering by a combination of friction and shock processes) [Spray and Thompson, 1995; Spray, 2010]. Based on the growth rate and melting along the surface (carbonization), the blades documented in our experiments provide an analog for the generation of pseudotachylytes at much larger scales where they become exposed in eroded central peaks.

On planetary surfaces, large oblique impacts typically display extended, linear or breached central peaks. The observed shear induced failure planes beneath the crater floor in our experiments may provide new insights into the mechanism of their formation. Specifically, shear planes developed below the crater during the earliest stages of coupling create zones of weakness that control uplift.

A long list of parameters can affect subsurface damage following oblique impacts, including impact angle and velocity, projectile type, and target material and geometry. Planetary surfaces in the inner the solar system often present layered targets (e.g, ice, mega-regolith, or sedimentary surfaces over crystalline bedrock). The presence of these low-impedance layers (where impedance is defined as the product of the uncompressed density and sound speed) over bedrock can affect energy transmission into the

subsurface, thereby reducing crater size and subsurface damage. Chapter 3, then, focuses on the effects of a layered target on subsurface damage and pressure evolution in the substrate. Experimental results coupled with laboratory and planetary-scale models demonstrate that even a thin surface layer mitigates peak pressures in the subsurface, along with the resulting damage.

Chapter 4 continues the exploration of the effects of low-impedance surface layers on the subsurface damage as measured in the field (e.g., shock indicators in minerals). The results are applied to two specific terrestrial examples: The Upheaval Dome in Utah, and the Rock Elm impact structure in Wisconsin. Weakly shocked quartz grains within the central regions of both these structures confirmed their impact origin after many years of debate [French *et al.*, 2004; Buchner and Kenkmann, 2008]. In both cases, removal of surface sediments made identification of the impact structure more difficult by erasing obvious mineralogic signatures and ubiquitous shock features created closer to the impact point. Reconstruction of the target and evaluation with large-scale CTH models indicate that sufficiently thick surface sediments can reduce the peak pressures generated by an oblique impact. Once the surface sediments are removed, little to no shock features in minerals remain. Peak pressure magnitudes predicted by the model are consistent with field observations from Rock Elm and the Upheaval Dome.

Finally, Chapter 5 extends this study to the case of damage created by oblique impacts into a sphere with applications to failure zones within asteroids. We present the first time-resolved study of damage growth in spherical targets. Damage within a spherical target will be different than a planar target due to the interaction of the shock wave with the curved surface [e.g., Rinehart, 1960]. Thus, experiments and small-scale

CTH models reveal details about deep, antipodal failure structures. Small-scale model results indicate that localized planes of failure within the target are due to shear processes, in addition to the observed tensile failure. Large-scale CTH models then extrapolate these insights to better understand observations of damage structures on asteroids.

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FIGURE CAPTIONS

Figure 1. Schematic of viewing geometry in laboratory experiments. Two high-speed cameras track the evolution of subsurface damage in PMMA targets following impact. One camera is focused on the side of the target block and tracks damage growth along the trajectory. The second camera is focused on a mirror uprange of the target block, which shows damage growth perpendicular to the trajectory. All experiments are documented using this camera geometry at frame rates of 250,000-500,000 frames/second.

FIGURES

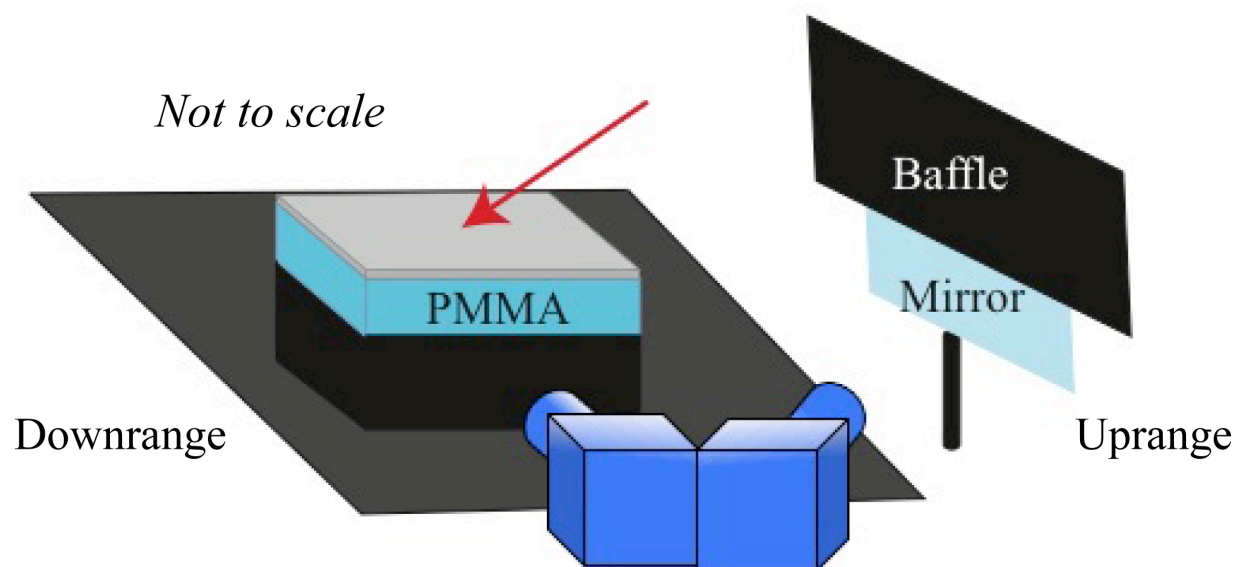


Figure 1

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Chapter 1

Exploring the role of shear in oblique impacts: A comparison of experimental and numerical results for planar targets

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Abstract - Oblique impacts produce asymmetric damage patterns due to asymmetric, directed shock waves; these patterns are seen for both laboratory and planetary scale craters [Schultz and Anderson, 1996; Dahl and Schultz, 2001]. Previous laboratory and computational studies of impact-induced damage have focused mainly on tensile failure following hypervelocity impacts. Though extension plays a significant role in impact-induced damage, it is widely accepted that shear failure also occurs during hypervelocity impacts. Shear failure occurs over a variety of scales both during and after impacts [Spray and Thompson, 1995; Schultz, 1996; Kenkmann, 2002]. Here we examine this process in more detail for oblique impacts. Experiments not only provide a general view of small-scale processes (including damage patterns in their final form), but also can be difficult to relate to larger impacts with confidence, even though similarities can be documented [e.g., Schultz and Anderson, 1996]. Detailed computer models provide complementary information. Although they detail underlying processes during crater formation, they do not always contain adequate constitutive models, thereby requiring simplifying assumptions. A comprehensive model taking into account deformation following failure of rocks is still unavailable, which limits conclusions based solely on numerical simulations. Consequently, a combination of models and experiments must be used. Impact experiments into planar polymethylmethacrylate (PMMA) targets at small scale are examined in an attempt to constrain the sequence, location and style of failure. Two- and three-dimensional CTH models (with identical conditions to the experiments) were computed using a variety of failure criteria in order to determine the parameter set that best matches the experimental results. High-speed imaging recorded the sequence and location of failure within various PMMA targets, which was then compared with

results from theoretical models. The CTH models provide critical details about specific failure style and indicate only minimal failure due to extension following the impact except for tensile failure at the base of the block. Instead, shear failure dominates below the crater. While the CTH hydrocode models generally match the extent of the damaged region, some differences remain. Projectile properties (density, composition, size) for impacts with the same kinetic energy affect the extent, style, and growth of damage in a given target. This includes differences in degree of uprange damage, subarcuate fractures, and sub-parallel failure planes. Comparisons between experiment and hydrocode results reveal that projectile failure (even at hypervelocity) contributes to the observed differences.

INTRODUCTION

Oblique impacts produce asymmetric damage patterns due to directed shock waves; these patterns are seen for both laboratory and planetary scale craters [e.g., Gault and Wedekind, 1978; Bischoff and Oskierski, 1988; Schultz and Gault 1990a; Schultz and Gault, 1990b; Schultz and Anderson, 1996; Pierazzo and Melosh, 2000; Dahl and Schultz, 2001; Tsikalas, 2005; Scherler *et al.*, 2006]. Previous computational studies of impact-induced damage focused primarily on tensile failure following hypervelocity impacts. Specifically, Smooth Particle Hydrodynamics (SPH) hydrocode models (as well as CTH models) focused on primarily extensional processes and failure [e.g., Nakamura and Fujiwara, 1991; Benz and Asphaug, 1994; Benz and Asphaug, 1995]. Senft and Stewart [2007] examine the possible locations of shear failure using the CTH hydrocode,

whereas other studies by Ivanov *et al.* [1997] used the SALE-2D code to examine tensile failure around impact craters, as well as of the projectile.

Although extension plays a significant role in impact-induced damage, shear failure also must contribute [Spray and Thompson, 1995; Kenkmann, 2002; Stickle *et al.*, 2009]. Results of SALE-2D hydrocode calculations indicate large regions fail in shear during an impact, whereas only small regions near the surface of the target fail in tension [Ivanov *et al.*, 1997]. Separate studies by Senft and Stewart [2007] using the CTH hydrocode indicate regions dominated by shear failure beneath vertical impacts. Experimental results also support the presence of shear-dominated failure regions [Gupta, 1980; Schultz, 1996; van der Bogert *et al.*, 1998; Dahl and Schultz, 2001; van der Bogert *et al.*, 2003]. Though previous studies have discussed this failure in broad terms, here we examine this process in more detail for oblique impacts in order to constrain their location and sequence, as well as extent of damage directly following hypervelocity impacts.

Experiments allow documenting processes at small scales and reveal damage patterns in their final form, which then can be compared with features at large scales, while detailed computer models provide extrapolation to large scales. Because such models do not always contain sufficiently sophisticated constitutive models, however, simplifying assumptions must be made. For example, a comprehensive model that takes into account deformation following failure of rocks is still unavailable, thereby limiting some conclusions drawn just from numerical simulations. Consequently, comparing results from both models and experiments more fully reveals details of the process.

EXPERIMENTAL APPROACH

The modes of failure due to a hypervelocity impact (and how this failure is manifested at large scales) can present a challenge for hydrocodes. The most recent version of the CTH hydrocode [McGlaun *et al.*, 1990] includes adaptive mesh refinement in order to minimize computational time while resolving small-scale structures. This improvement provides a strategy to test conclusions about failure modes and dominant processes drawn from small-scale laboratory experiments. Here impact experiments into planar polymethylmethacrylate (PMMA) targets at small scale are compared with CTH models in an attempt to constrain the sequence, location and style of failure.

The transparency of PMMA allows a clear view of the evolving failure patterns within the target [e.g., Schultz and Anderson, 1996]. Fortunately, room temperature PMMA also has mechanical properties similar to those of brittle rocks in the upper crust [de Joussineau *et al.*, 2003]; this makes it an ideal material for comparison to geologic materials. In addition to its mechanical properties, PMMA exhibits birefringence, which permits analog studies of dynamic failure processes in rock [Rosakis *et al.*, 1999; Rosakis 2002; de Joussineau *et al.*, 2003; Rosakis *et al.*, 2004; Rosakis *et al.*, 2008; Misra *et al.*, 2009]. These experiments were performed at room temperature, taking advantage of the brittle nature of PMMA. To determine how these results apply to more ductile materials, future studies may be done on heated PMMA or on other transparent plastics that are ductile at room temperature (i.e., Polycarbonate).

CTH calculations reveal that shear failure dominates failure in PMMA at laboratory scales [Schultz and Crawford, 2008; Stickle *et al.*, 2009]. Shock-induced tensile failure in PMMA at laboratory scales can be shown to resemble failure in basalt, although shear

failure is significantly reduced. Nevertheless, hydrocode models reveal that shear becomes more important at larger scales [Schultz and Crawford, 2008]. Consequently, PMMA provides an ideal analog material to look at the effect of shear damage during hypervelocity impacts, as well as the interaction between shear and tensile stresses. Planar targets allow calibration of the relative role of various processes, thereby providing a benchmark between the theoretical models and experimental data. Such comparisons also provide a basis for the comparisons between experiments and CTH models of more complicated processes, e.g., within spherical bodies [Schultz and Crawford, 2008; Stickle *et al.*, 2009].

Experiments were performed at the NASA Ames Vertical Gun Range (AVGR) at the NASA Ames Research Center in order to address the style and sequence of failure occurring underneath oblique impacts. The AVGR is a two-stage hydrogen light gas gun, which can launch projectiles at velocities up to 7 km/s (mass < 0.1 g) over a range of impact angles from 15 degrees above horizontal to vertical, (in 15-degree intervals) while leaving particulate targets horizontal. For this study, experiments used 15 x 15 x 6 cm and 15 x 15 x 5 cm blocks of PMMA with projectiles impacting at an angle of 30 degrees above the horizontal with velocities ranging from ~3.8 - ~6.3 km/s. High-speed imaging (250,000-500,000 frames/sec) documents the sequence and location of failure due to impact. The PMMA targets rested on a Styrofoam block in order to minimize free-surface effects at the base of the block. Evolution of the damage growth was measured through the side of the target over a range of azimuths extending from the point of impact (Figure 1, Figure 4). Material was considered “damaged” within the opaque region.

Corresponding three-dimensional CTH models were computed using identical conditions to the experiments. The calculations use a Mie-Grüneisen equation of state (EOS) for the Pyrex impactor [Marsh, 1980], PMMA target and Styrofoam base (both available within the CTH package). PMMA has a shock-induced phase transition at ~ 25 GPa, and the Mie-Grüneisen EOS is a good representation for PMMA below this transition. At pressures above the transition, the EOS still provides rough agreement and it can be used with confidence up to pressures of ~ 100 GPa. Because we are concerned with material away from the impact point at much lower pressures, this EOS provides a valid representation of our material. Two separate failure criteria were used. The Johnson-Cook Fracture model illustrates the relative roles of shear failure and extensional failure (“spallation”). Extensional failure occurs when the stresses exceed the tensile strength of the material. Shear failure occurs when the stresses exceed the yield strength of the material and the material exceeds a specified amount of plastic strain. The models used in these calculations assume linear, isotropic elasticity, and von Mises plasticity with an associated flow rule that the plastic strain rate is always normal to the yield surface.

The Pyrex projectile was assumed to behave like a geologic material, with a pressure yield surface that incorporates thermal softening and density degradation. Currently, this is sufficient in modeling the basic behavior of the projectile breakup during impact. A slightly more complicated strength model was needed to model impact damage into the PMMA. Unfortunately, it is difficult to model both shear and tensile failure of PMMA concurrently in CTH today. Therefore, two separate strength models for PMMA are considered. Damage by extensional failure occurs when the maximum allowable tensile

stress is exceeded; spallation is represented with this model. Shear-induced damage follows the Johnson-Cook Fracture (JCF) model. JCF is a scalar damage model for predicting the failure of materials where the failure criterion is based on equivalent plastic strain as a function of pressure, temperature, strain rate and loading path. While this model only predicts damage involving shear deformation, it is typically used in conjunction with the spall model for predicting failure of damaged material or due to excess hydrostatic tension. However, for increased understanding of PMMA failure, we find it useful to treat shear and extensional failure separately and not try to convolve the two phenomena. In the JCF model, a scalar damage parameter, D , is calculated in each cell: D ranges from 0 (pristine, undamaged material) to 1 (completely damaged material) and failure occurs when $D=1$. The damage parameter is calculated according to:

$$\frac{dD}{dt} = \frac{\dot{E}}{E_F} \quad (1)$$

where $\dot{E}$ is the equivalent plastic strain rate and E_F is the local value of strain to fracture, which is calculated by:

$$E_F = (D_1 + D_2 \exp\left(\frac{-D_3 p}{Y}\right)) * (1 + D_4 \ln(\dot{E})) * (1 + D_5 T_{\text{hom}}) \quad (2)$$

where D_1 - D_5 are constants, p is pressure, Y is the local yield stress and T_{hom} is the homologous temperature, defined by:

$$T_{\text{hom}} = \frac{T - T_{\text{room}}}{T_M - T_{\text{room}}} \quad (3)$$

where T_M is the melting temperature of the material. Once the material has failed, the yield strength is then assumed to be zero. The failure criterion is set, here, in terms of equivalent-plastic-strain to failure, which is represented by D_1 . D_2 - D_5 are set to zero in

these models. A parameter study comparing numerical results to experiment determined the appropriate values for D_1 .

All calculations are conducted in 3D rectangular coordinate system, which allows us to examine oblique impacts in detail. AMR is used to resolve small-scale detail within the problem, without necessitating a high-resolution mesh across the entire problem, which is computationally expensive. For the results examined in this study of laboratory scale impacts, the simulations have a maximum resolution of 0.09 cm (~6 cells across the projectile). Mass-less, Eulerian tracers are used to track the history of material beneath the impact point throughout the problem.

RESULTS

Experimental Results

High-speed imaging captures the sequence and location of failure zones that can be compared to theoretical models. Immediately after impact into PMMA blocks, crater damage first occurs uprange from the point of first contact, growing downward and uprange. In general, between 10-12 μ s after impact a “tongue” of damage begins to form downrange, as an asymmetric damage zone grows outward and downward. As this tongue grows, it curves downward and around the main central damage zone, thereby increasing the asymmetry downrange from the impact point. The plane wraps around the damaged region, and is significantly offset downrange (Figure 1). A zone of damage on the bottom of the block appears ~20-25 μ s after impact, and grows outward. Damage growth ends approximately 40 μ s after impact. Figure 1 shows a time-sequence of

damage growth following a 30 degree impact of a 0.635-cm Pyrex sphere into the PMMA block at ~ 5 km/s.

This is a typical sequence and morphology of subsurface failure. Although some variation occurs for different impact velocities, this generally affects the final extent of damage, rather than the overall morphology. Impacts with a PMMA projectile into PMMA blocks, for instance, result in a dramatically reduced damage zone extent as compared with damage from aluminum or Pyrex projectiles. Even for impacts with approximately the same kinetic energy, the damage zones are morphologically similar, but with different overall extent (Figure 2). Aluminum projectiles induce the greatest downrange damage, and the damage extent is greatest overall. Pyrex projectiles also create a distinct and well-defined downrange, subarcuate tongue of damage. PMMA projectiles at the same impact velocities generate similar, though less distinct, features. Furthermore, damage along the trajectory is manifested in slightly different ways depending on projectile type. Linear features and sub-parallel planar damage features appear clearly for aluminum projectiles, but are increasingly subdued for lower density and weaker projectiles [Stickle and Schultz, 2010]. Impacts with identical kinetic energy, however, produce nearly identical overall damage extents, even for different projectile types. Though minor differences in damage growth are seen between aluminum and Pyrex projectiles, overall the damage extent is the same at all azimuths. Nevertheless, differences in damage do occur downrange and in the subsurface where failure planes parallel the impact trajectory. These differences are inferred, then, to be due to failure of the projectile, rather than just impact energy. Projectile effects also affect the backside spallation in the target. Figure 2a and 2b show impacts of PMMA and Pyrex projectiles,

respectively, and have impact energies within 20% of each other. However, the PMMA-PMMA impact results in a backside target spall where the Pyrex-PMMA impact does not. The damage is greatest along the trajectory (30 degrees) and directly below the impact point (90 degrees) due to the directed shock wave. Up-range of the impact point, the damage zone grows the least. Typical uncertainties in damage measurements are shown in Figure 3a.

CTH Results

Two different proxies can be used to map the amount of failure below the impact point: contours of the damage parameter (D) from the JCF model; or, equivalently, contours of plastic strain. These are equivalent proxies, since a value of $D = 1$ corresponds to material subjected to equivalent plastic strain exceeding the yield stress of the material. While these criteria result in equivalent maximum damage, structure beneath the impact point is only resolved when examining contours of strain. Strain evolution tracked in CTH (comparable to Figure 1) is shown below (Figure 4) for failure set at 10% plastic strain. The reasoning for this particular strain limit is explained below. The damage extent ($D = 1$) was tracked along five different azimuths through time. In addition, five separate CTH calculations were run with differing failure criteria. This reveals how well the calculation reproduced the observed subsurface damage in the experiments. Initial material properties were chosen as the static strength and strain-to-failure for PMMA from online material databases ($\sigma_Y = 120$ MPa, 5% strain to failure) [polymerweb.com] and adjusted from there. Figure 5 shows the five different combinations of yield strength and shear-to-failure that were considered.

Identical simulations at multiple resolutions revealed the effect of mesh resolution (Figure 3b). The highest resolution model had a maximum resolution of 0.04 cm (~13 cells across the projectile). The higher resolution model appears slightly weaker and therefore has a slightly larger final damage zone. Although interesting, this weakening does not affect the basic results of this study that focus on the primary style of failure. These results are sufficiently resolved to study the comparison between various failure criterion and experimental damage.

The CTH simulations shown here predict rapid initial damage growth directly following impact, with the maximum damage reaching a final size between 10 - 20 μ sec after impact (Figure 5). The damage extent is a function of the material properties assumed for the PMMA, but the growth rate does not appear to be controlled in the same way. These results are representative, and the same differences are seen for all the runs, with all projectile types.

DISCUSSION

The style of failure in regions below the impact point can be understood by comparing models and the experiments. As the CTH models show, the subsurface damage is due to plastic failure and is likely due to shear failure. While previously demonstrated for varying geometries and impact conditions [Schultz and Crawford, 2008; Stickle *et al.*, 2009], here we use high-speed imaging to resolve the evolution of damage growth in the AVGR experiments in order to document the process.

Shear yielding in PMMA can occur in diffuse shear deformation zones [Bowden, 1973], and this is consistent with the rate of damage growth in the experiments. The

limiting velocity of Mode I (tension) cracks should be the Rayleigh wave speed, but opening mode cracks rarely grow at this speed. In contrast, Mode II and Mode III shear cracks propagate more quickly than opening cracks. The sound speed and the shear wave speed, respectively, limit growth of these cracks [Ravi-Chandar *et al.*, 2000]. The sound speed in PMMA is ~ 2.75 km/s [Carlson *et al.*, 2003], whereas the shear acoustic velocity is ~ 1100 m/s [Harding and Du, 1997]. The Rayleigh wave speed, however, is ~ 950 m/s [Ravi-Chandar *et al.*, 2000]. The damage zone propagation speed can be estimated from the slope of the damage growth through time curve, along the portion from time=0 to when the damage reaches a maximum value, and this can be used as a proxy for a minimum crack growth speed. The results are shown in Tables 1 and 2 for Pyrex and aluminum projectiles, respectively. For all azimuths except the uprange surface, the damage propagation speed is consistent with shear failure. The uprange surface cracks are expected to be a result of extension, consistent with the observed velocities. Future detailed studies are necessary to fully understand the damage zone propagation, but this interpretation is consistent with the failure mode illustrated by the CTH simulations.

In order to match the damage zone extent from CTH models with experimental results, material strength and strain to failure must be increased beyond those originally assumed. However, no material adjustment allows matching the initial damage zone growth at early times. This is likely due to the hydrodynamic nature of CTH and the way that the failure model is tracking the data. The failure model effects are manifested in two distinct ways: a positive feedback in damaged materials and physical limits on crack growth in real materials. In the CTH model, the JCF model assumes failure when the damage parameter equals one and the material loses all strength. Consequently, this

could affect predictions for further damage. Since failed regions can no longer resist shear, the regions immediately surrounding them are preferentially (and in some cases unrealistically) loaded. In reality, a failed material will still exhibit some resistance to shear, acting to limit the stress transferred to neighboring materials. Moreover, the failure model used here does not take into account limiting crack velocities, thereby predicting unphysical growth of the damage zone. In natural materials, failure is not instantaneous once failure conditions have been met. Thus, in order for CTH to accurately predict the time necessary for damage growth, limiting velocities must be included.

One goal of this study is to identify specific processes that are responsible for contrasts in the target response for different impactor variables. Two features provide important clues. First, spallation off the backside free surface depends on projectile type (Figure 2). Catastrophic failure of Pyrex projectiles occurs after first contact, and surviving fragments completely decouple from the target, thereby reducing the total energy coupled to the target. PMMA and aluminum projectiles, however, decapitate (shear) but re-impact the target downrange nearby [Schultz and Gault, 1990a]. Consequently, Pyrex projectiles generate reduced shock pressures that reach the backside of the target below. Second, the downrange “tongue” of damage appears independent of projectile type. This feature is interpreted as a result of the shallow, downrange-directed peak-shock pressure, which is generated at first contact (before decapitation) and is unrelated to projectile fragmentation. Consequently, this feature should be the same for different projectile types. The current CTH models (Figure 6) do not replicate this feature.

The uprange damage was never successfully matched even though CTH can reasonably predict the extent of damage downrange. The computer simulations consistently under-predict the amount of uprange damage seen in the experiments, perhaps reflecting limitations in the failure model used here. New models are being developed to include shear and extensional failure concurrently within CTH [Senft and Stewart, 2007], but this is not a failure model option currently available. Therefore, here, we chose to model failure due to plastic strain, which will not capture purely extensional damage. From the damage growth velocities, the uprange surface cracks are most likely extensional cracks due to free-surface effects on the target block, a process that would not be captured by the JCF model. When a failure criterion to examine extension alone is implemented, however, failure is consistently underpredicted as well. This leaves a discrepancy between the models and the experiments.

CONCLUSIONS

While computer models provide a powerful tool for interpreting complicated physical processes, experiments allow testing their validity and reveal critical details. Here, we illustrate that shear deformation dominates subsurface failure but an appropriate failure model is needed in order to reproduce the final structures and subsurface damage seen beneath experimental oblique impacts. Although subtle, such differences have consequences when scaled to planetary impacts. Subsurface damage in oblique impacts should include both shear and extensional failure concurrently, and the possible consequences of decapitation and re-impact by the projectile [Schultz and Gault, 1990a; Schultz and Gault, 1990b; Schultz and Anderson, 1996]. We also find that the failure

style of the projectile can affect coupling with the target, which may not be fully captured in CTH models. These processes contribute to (and limit) accurate prediction of damage growth and arrest.

Acknowledgements

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TABLES

Table 1. Average damage zone propagation velocity for Pyrex projectiles

Run number	Impact Velocity [km/s]	30° damage growth [m/s]	90° damage growth [m/s]	30° damage growth [m/s]	UR	UR Surface damage growth [m/s]	DR surface damage growth [m/s]
090627	3.58	1766	1058	1169		835	1559
090620	4.42	1782	1336	1169		508	1354
090619	5.02	1838	1211	1253		668	1500
090622	5.15	1931	1336	1243		1055	1452
090618	5.21	1579	1203	1671		668	1324
081111	5.5	1848	1422	950		640	971
090613	6.43	1549	1133	1361		971	1643

Table 2. Average damage zone propagation velocity for aluminum projectiles

Run number	Impact Velocity [km/s]	30° damage growth [m/s]	90° damage growth [m/s]	30° UR damage growth [m/s]	UR Surface damage growth [m/s]	DR surface damage growth [m/s]
090626	3.87	1475	1222	1284	983	1955
090623	4.44	1543	1200	1735	792	1389
090614	4.88	1875	1038	1395	1133	2517
090612	5.49	1450	1094	1073	1075	2566

FIGURE CAPTIONS

Figure 1. Time sequence of damage growth following the 30 degree impact of a ¼” Pyrex sphere into a PMMA block at ~5 km/s. Up-range damage appears first, and the zone grows downward and down-range. About 25 μ s after impact, extensional damage develops on the bottom of the target. Red arrow shows impact trajectory. Blue lines show the top and bottom surface of the block, 6 cm apart; the size of the projectile is shown for comparison. CTH simulations indicate that shear failure dominates beneath the crater, and small region of extensional failure is seen at the bottom of the target, offset down-range.

Figure 2. Final damage extent resulting from 30 degree impacts of a) 0.635 cm PMMA sphere at 5.43 km/s, b) 0.635 cm Pyrex sphere at 3.58 km/s and c) 0.635 cm aluminum sphere at 3.87 km/s into 5 cm PMMA blocks. Blue lines show top and bottom of block for reference. The energy of the PMMA impact is between that of the aluminum and Pyrex.

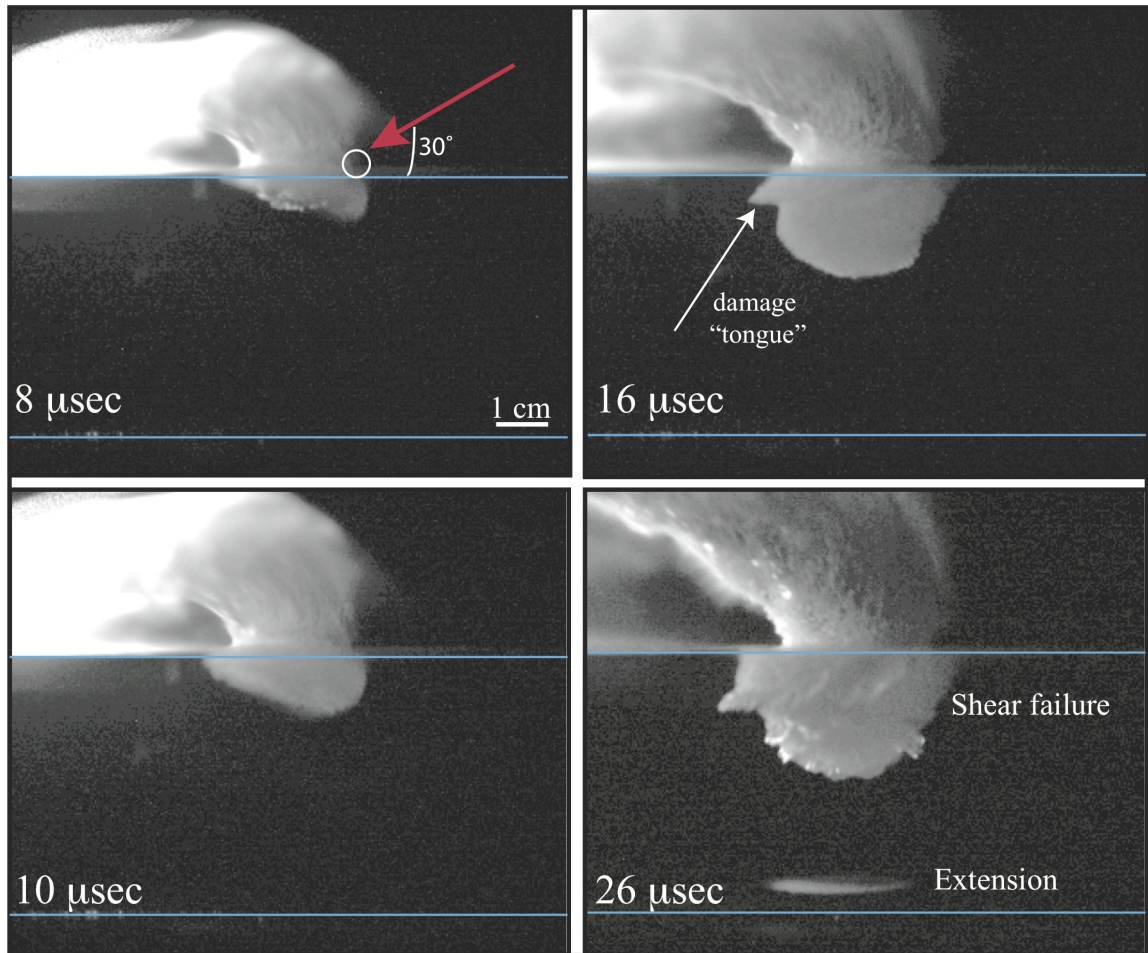
Figure 3. a) Standard error bars from measurements of the damage zone growth through time. Curves show damage zone extent through time for various azimuths, measured from the impact point. Projectile was 0.635 cm solid Aluminum, impacting a 2” PMMA block at 3.87 km/s. See Figure 4 for a diagram defining these azimuths. b) Results of a resolution test for CTH simulation of 0.635 cm Pyrex projectile into a 2” PMMA block at ~5 km/s and an impact angle of 30 degrees above horizontal. The damage was measured along the 30-degree azimuth. High-resolution simulations appear slightly weaker.

Figure 4. Time sequence, showing damage evolution within the PMMA target through time. Damage is represented using plastic strain, and material failed at 10% plastic strain. Simulation models an impact of a 0.635 cm Pyrex projectile at 5.02 km/s into a 5-cm PMMA block at 30 degrees. The PMMA block is resting on top of a Styrofoam base to minimize free-surface effects. Small amounts of strain appear in the foam approximately 16 μ sec after impact.

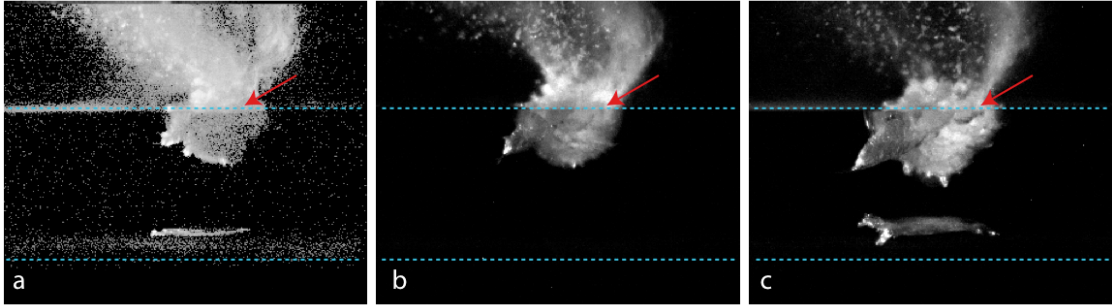
Figure 5. Comparison of CTH models and experimental data. Impact velocity: 5.02 km/s, impact angle: 30 degrees, projectile: 0.635-cm Pyrex sphere. CTH model material properties were varied in order to match the final damage zone extent seen in the experiments. Measurements at 5 different azimuths are shown: a) 30 degrees, b) 90 degrees, c) 30 degrees up-range, d) up-range surface, and e) down-range surface. f) Schematic showing the locations and geometry of the measured azimuths.

Figure 6. CTH comparison to experimental results of 0.635 cm Pyrex sphere impacting into a 2” PMMA block. Images shown are 50 μ sec after impact, following the “steady-state” damage extent. Note the discrepancy in down-range failure even though the overall damage extent is similar.

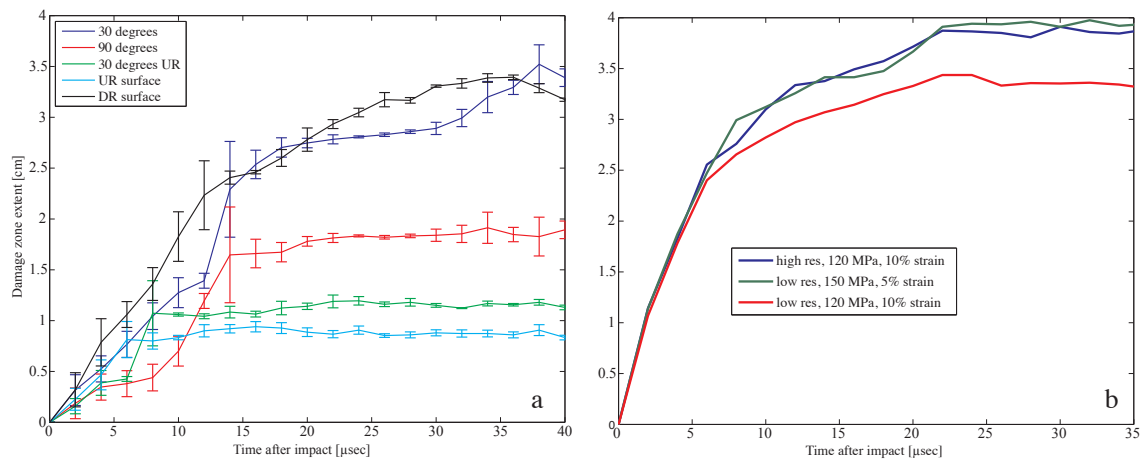
FIGURES



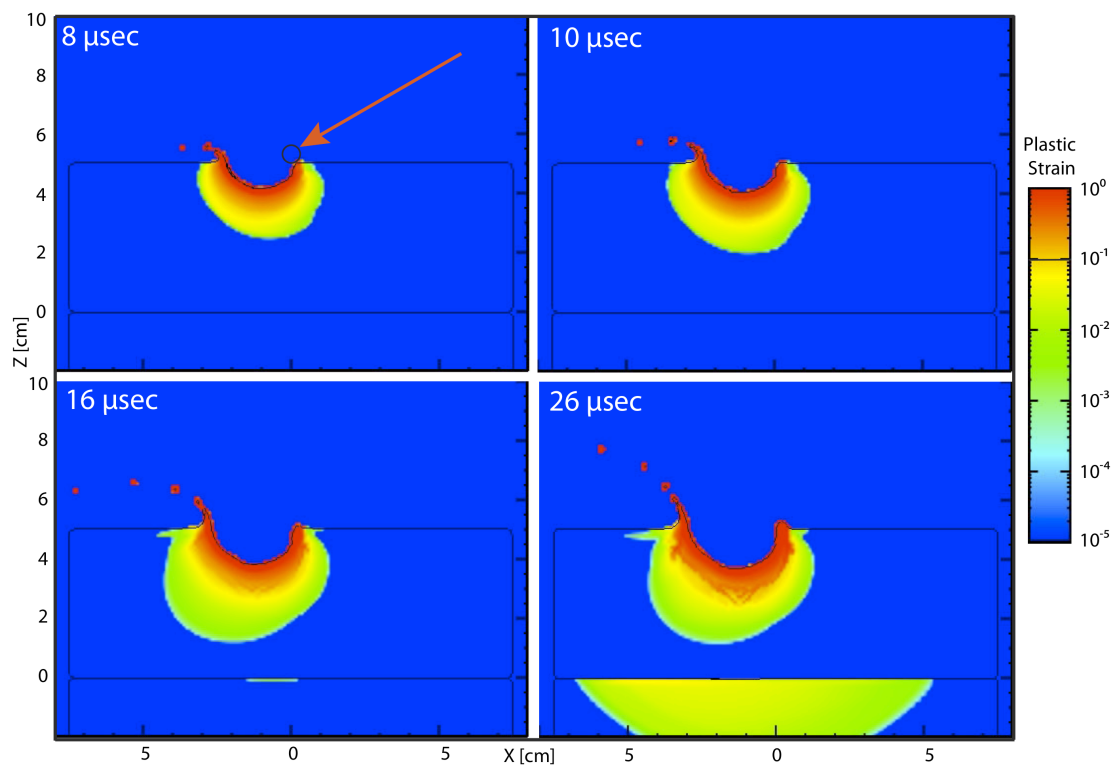
Masters Thesis, Figure 1



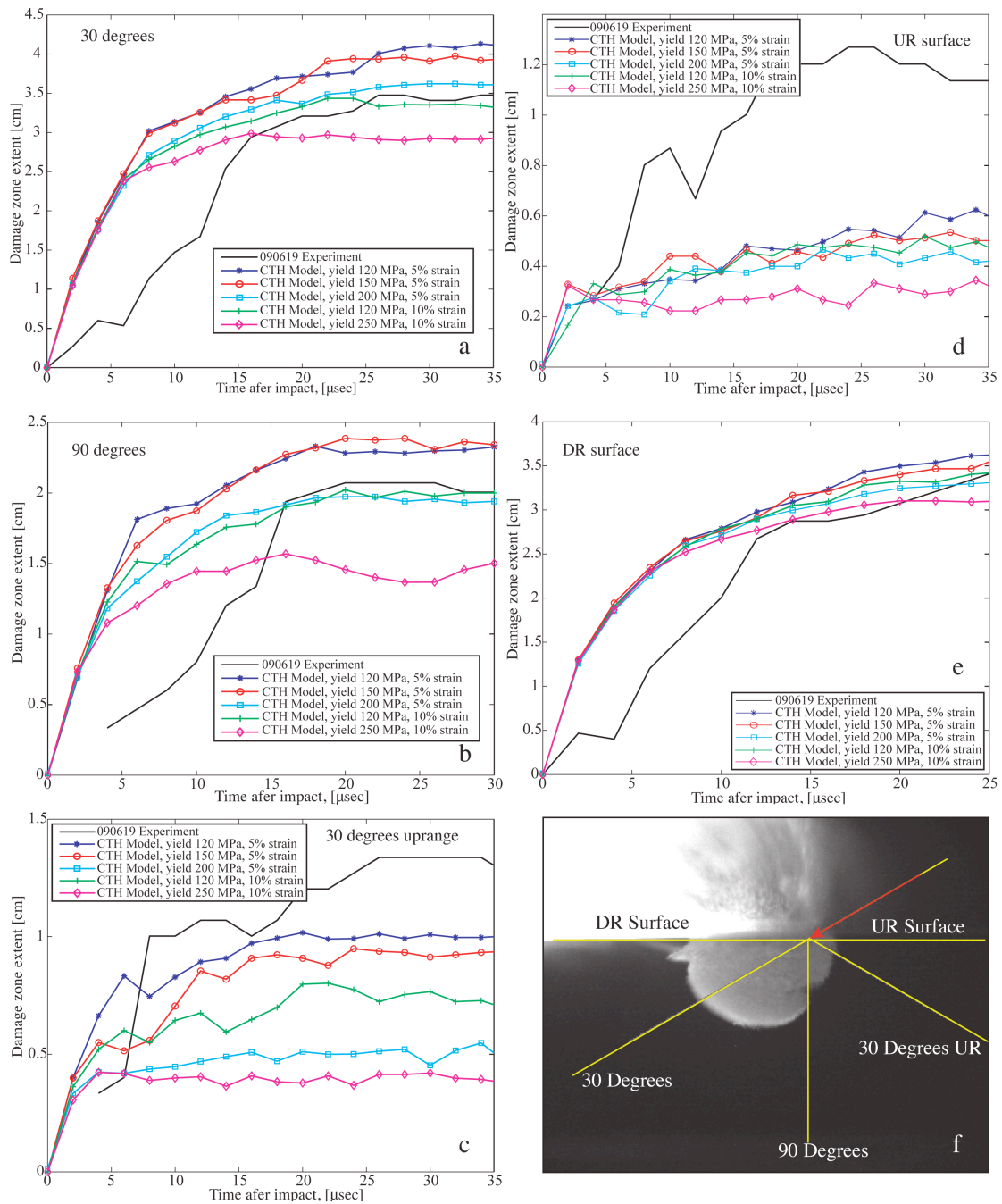
Masters Thesis, Figure 2



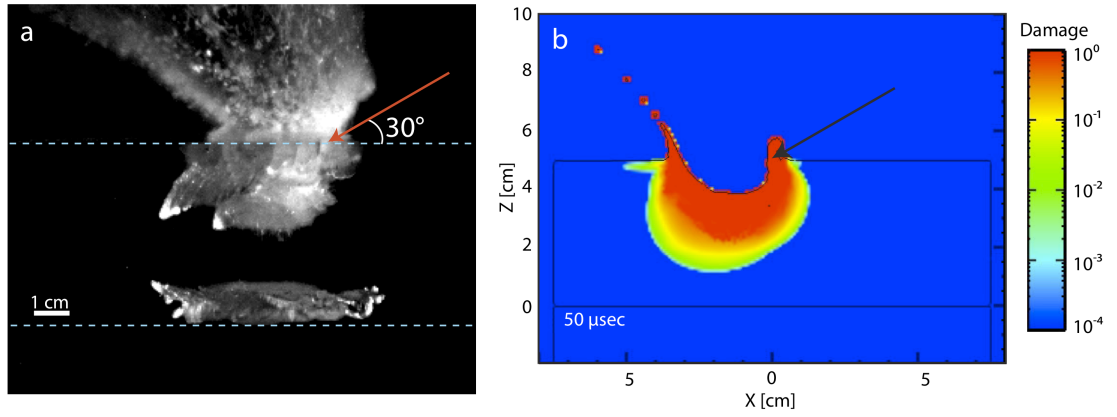
Masters Thesis, Figure 3



Masters Thesis, Figure 4



Masters Thesis, Figure 5



Masters Thesis, Figure 6

Chapter 2

Discrete shear failure planes resulting from oblique hypervelocity impacts

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Abstract - A combination of laboratory and numerical experiments examines the role of shear localization in subsurface damage following very oblique (15-30°) hypervelocity impacts. Laboratory experiments reveal subsurface damage planes (“blades”) parallel to the impact trajectory for highly oblique impacts (15-30°), which are characterized by unique surface textures relative to other failure regions. Observations of growth rate and surface texture of the damage planes combined with three-dimensional CTH simulations indicate that the blades are the result of frictional processes during localized shear deformation. Laboratory experiments also reveal that impact angle and projectile failure plays a role in the development of these blades: aluminum projectiles result in distinct along-trajectory blades for both 15° and 30° impacts, whereas the blades are weakly developed for Pyrex projectiles and non-existent for PMMA projectile. The blades form early in the cratering process and are signatures of the projectile momentum being transferred into the target. Based on the growth rate, and melting seen along the surface of these damage planes, the blades provide an analog for the generation of pseudotachylytes during the early stages of impact crater formation. These discrete failure planes may also provide new insight into linear or breached central peaks on planetary surfaces.

INTRODUCTION AND BACKGROUND

Traditionally, subsurface damage following hypervelocity impacts has been explained by yielding and/or melting following directed shock waves. Following extreme compression during passage of the shock wave, the material will unload rapidly. Thus extension and tensional failure were thought to dominate beneath impact craters [e.g., Melosh 1989; Polanskey and Ahrens, 1990; Ahrens and Rubin, 1993; Benz and Asphaug,

1995]. This damage leads to weakening of the material, which has consequently been dubbed “shock weakening”.

Directly following an impact, a system of shock waves transfers energy from the projectile into the target. The high shock pressures can exceed material strength, which results in yielding and damage accumulation. At the target surface, an expansion fan develops in order to maintain equivalent stress across the boundary, thereby causing excavation of the target material [Gault *et al.*, 1968]. The tensile stresses developed at the boundary also can lead to dynamic failure and spallation. A process especially important at small scales (i.e., small targets in laboratory experiments) occurs near the end of the cratering process as waves begin to “bounce around” within the target. Interference of rarefaction waves then could lead to additional dynamic failure within the target, which in turn can lead to massive tensile failure of the material.

The classic scenario focusing just on shock compression and rarefaction, however, is likely incomplete because experimental and numerical studies demonstrate that shear deformation is also important in subsurface failure, especially for highly oblique impacts (i.e., 15-30°) [van der Bogert *et al.*, 2003; Collins *et al.*, 2004; Senft and Stewart, 2009; Stickle and Schultz, 2011]. Consequently, shear and frictional processes also must be considered in some detail in order to fully understand target damage. Because one quarter of all impacts occur at angles less than 30° [Gilbert, 1893; Shoemaker, 1962], frictional processes become increasingly important for an understanding of damage from impact processes.

Laboratory experiments also reveal that shock heating is insufficient to produce all of the melt following impacts, frictional processes are also required. Van der Bogert *et*

al. performed experiments to show that high strain-rate deformation and frictional melting are extremely important processes in impacts, especially at low shock pressures characterizing lower speed impacts in the asteroid belt [van der Bogert *et al.*, 1998; 2003]. In addition, they showed that black chondrites are darkened due to frictional processes during high strain-rate shear [van der Bogert *et al.*, 1998], which is in contrast to the generally accepted view that shock heating is the cause of impact melt and the interpretation of veins found in meteorites as “shock veins” [e.g., Heymann, 1967; Scott *et al.*, 1999, Pierazzo and Melosh, 2000]. Similar results were found by Reimold *et al.* [2003] when examining veins in the H4/5 meteorite Thuathe. The authors conclude that narrow, black veins resulted from frictional melting without locally enhanced shock pressure. Similarly, Kenkmann *et al.* [2000] found that there was significant evidence for shear deformation following shock experiments into a variety of lithologies, and that localized melt veins were formed by shear processes and not by shock-compression-generated heating because the shock temperatures were not high enough. They further noted that deformation localization and melt production have important ramifications for rheology and strength of the target material following impact. Langenhorst *et al.* [2002] continued with similar experiments in olivine, showing that shock veins in meteorites, which were previously thought to be due to shock melting [Heymann, 1967; Scott *et al.*, 1991], are actually caused by shear heating in Mode II cracks.

These experiments show that shock waves induce shear stresses (with corresponding shear deformation) during decompression of the material. Shear deformation then localizes into discrete “faults”. Such a process is especially true in geologic materials that contain impurities and pre-existing structure at small scales (such as grain and phase

boundaries or crystal defects) or at larger scales such as layering or tectonic features [Kenkmann *et al.*, 2000; Barnouin-Jha *et al.*, 2005; Barnouin-Jha *et al.*, 2007]. As a shock wave passes through an inhomogeneous target, interactions along interfaces between different rock constituents take place. Small-scale structure results in local impedance contrasts within the material and can lead to shock wave reflection and refractions as well as displacement along any kind of interface. The shock wave can further separate into a leading and trailing shock front, which causes shearing and tensile forces within the zone of the shock front offset [Gibson and Spray, 1998]. Frictional melting is then induced in solids when stress and strain are localized.

Frictional processes are important throughout the stages of crater formation, and not only following the shock wave. During the modification stage of crater formation, substantial amounts of shear failure occurs as over-steepened walls collapse and slide, creating super-fault structures and generating significant amounts of pseudotachylytes [e.g., Spray and Thompson, 1995]. Finally, low-pressure, high strain-rate conditions also display significant shear failure at smaller scales [e.g., van der Bogert *et al.*, 2003; Spray, 2010]; these are precisely the conditions expected in the subsurface following very oblique impacts.

Because of the complexity of the impact process, numerical models are necessary to gain a more complete understanding of damage and failure processes within the subsurface following an impact. Ivanov *et al.* [1997] used the SALE-2D hydrocode to model planetary-scale impacts on a variety of planets. In an earth impact, the lithostatic pressure suppresses tensile failure just below the crater, resulting in a large shear-failure region. A mixed-mode zone surrounds this region where tensile failure occurs after

incomplete shear failure. The authors argue, however, that shear failure will only be important in a very shallow region beneath the crater while tensile failure remains the dominant damage-forming mechanism. Other studies examine small-scale vertical impacts and identify shear-dominated regions beneath the crater [e.g., Collins *et al.*, 2004; Senft and Stewart, 2007].

Given that shear failure is prevalent beneath impact craters, the question becomes whether diagnostic markers of shear processes can be found within experiments and on planetary surfaces. Identifying shear failure in laboratory experiments provides a first step to identifying shear failure in large-scale planetary craters. Possible shear markers at large scales are pseudotachylytes [e.g., Spray, 1998] and linear or planar failure zones in complex craters on planetary surfaces. This paper details observations of experiments performed at the NASA Ames Vertical Gun Range (AVGR) to provide context for planetary surface observations. Experimental and numerical results are described in detail to provide context and interpretations for geologic observations on planetary surfaces. This study points to a possible mechanism for generation of subsurface frictional processes following very oblique impacts with ramifications for linear central peaks and pseudotachylytes.

METHODS

A combination of laboratory experiments and numerical models are used to assess and interpret subsurface damage morphologies following very oblique impacts. Such a strategy permits comparisons at laboratory scales in order to isolate and understand a

process before extrapolating to large scales, whether by interpretations or simple acceptance of the large-scale model.

Laboratory Experiments

Small-scale laboratory experiments performed at the NASA Ames Vertical Gun Range (AVGR), at the Ames Research Center in Mountain View, CA, reveal subsurface damage structures following very oblique (15-30° from horizontal), hypervelocity impacts. The AVGR is a two-stage light-gas gun able to fire projectiles at velocities up to ~7 km/s, depending on projectile size. A 2.5-m diameter vacuum chamber allows for a wide range of target types and sizes, and can be maintained at a vacuum level of 40 Pa (1 atmosphere is ~101 kPa) or filled with a variety of gasses to simulate planetary atmospheres. The gun rotates on a large A-frame, such that the impact angle can change from 0-90° in increments of 15°, allowing the target to remain oriented correctly with respect to gravity. This is important especially when particulate targets are used to study the cratering process, and provides a means to study oblique impacts into a variety of target materials.

For this study, planar polymethylmethacrylate (PMMA) targets were used to examine subsurface failure structures. PMMA was chosen as a target material for two reasons: 1) the transparency of PMMA allows damage evolution to be easily tracked and studied immediately following an impact, which is not possible in rocks or metals; and 2) PMMA is brittle at room temperature and high strain rates, with mechanical properties similar to the upper crust of the Earth [de Joussineau *et al.*, 2003; Rittel and Brill, 2008; Dorogoy *et al.*, 2010], making it an ideal analog for laboratory studies of dynamic failure

processes in geologic materials [e.g., Rosakis *et al.*, 1999; Li and Lambros, 2001; Rosakis, 2002; de Joussineau *et al.*, 2003; Rosakis *et al.*, 2004; Rosakis *et al.*, 2008; Misra *et al.*, 2009].

The transparency of PMMA, combined with high-speed imaging (up to 1 million frames per second) provides a method to track the evolution of failure in the target material. The targets were 15-cm x 15-cm cast acrylic blocks with thicknesses of ~5 cm. In order to minimize free-surface effects at the base of the target, the PMMA blocks were set on top of a Styrofoam block in the target chamber. The details for the experiments used in this study are listed in Table 1. The impact velocity ranged from ~3.5 km/s to 6.4 km/s, and the impact angle was either 15° or 30° from the horizontal. Projectiles were Pyrex, PMMA or aluminum spheres with diameters of 0.3175 cm – 0.635 cm. The PMMA target is considered “failed” within the opaque (white) regions. Following the impact experiments, some of the damaged targets were cut and polished to isolate damaged regions for further analysis.

CTH Models

The laboratory experiments are complemented by a suite of numerical simulations using the CTH hydrocode from Sandia National Laboratories [McGlaun *et al.*, 1990]. CTH is a multi-dimensional, multi-material, two-step Eulerian code capable of modeling large deformation, strong shock processes that is widely used in the study of planetary impact cratering.

All calculations in this study are conducted in a three-dimensional rectangular coordinate space, allowing us to examine oblique impacts in detail. The maximum

resolution for these simulations is 0.015 cm (21 cells per projectile radius (cpr)) near the impact point. Mass-less Lagrangian tracer particles are used to track material motion beneath the impact point and throughout the PMMA target.

Direct, 1:1 comparison models were used to reveal details about failure mechanisms and conditions within the experiments. The models have identical impact conditions to the experiments, and damage evolution is tracked at the same temporal and spatial scale. The Styrofoam base was modeled using a von Mises yield surface. The density of the material was measured prior to the experiments, and library coefficients were used for the other strength parameters in the model. Pyrex projectiles were treated as a geologic material, with a pressure-dependent yield surface incorporating thermal softening and density degradation, and aluminum projectiles were modeled using the Johnson-Cook model for rate-dependent plasticity [Johnson and Cook, 1983] with coefficients available within CTH libraries. To better understand failure modes in PMMA, extensional failure and failure due to shear processes are considered separately. The Johnson-Cook fracture model [Johnson and Cook, 1985] is used to illustrate regions of shear failure within the PMMA target. In general, the failure criterion is dependent on plastic strain to fracture as a function of equivalent plastic strain, pressure, temperature, strain rate, and loading path. To minimize the parameter space, we only consider failure as a function of equivalent plastic strain, neglecting pressure, temperature, rate, and loading path effects. This simplification allows failure to be measured only in terms of strain, which is more easily comparable to laboratory experiments. When the material experiences stresses higher than the yield strength, it will undergo plastic strain and begin to accumulate damage (D); a pristine, undamaged material will have $D=0$. Here, the PMMA targets were assumed to

have a yield strength of $\sigma_Y=120$ MPa based on dynamic experiments in PMMA [e.g., Dorogoy *et al.*, 2010] and previous work in Stickle and Schultz [2011]. After a user-specified value of strain, the material is assumed to fail ($D=1$), and the yield stress drops to zero. Failure is set to occur at 10% plastic strain, following a parameter study in Stickle and Schultz [2011]. Extensional failure occurs when the tensile strength of the material is exceeded.

Equations of State (EOS) are necessary to complete the equation set. The Mie-Grüneisen EOS is used for the PMMA target, Styrofoam base (both are available within CTH and library coefficients are used) and Pyrex impactor [Marsh, 1980]. Aluminum projectiles are represented using the semi-analytical ANEOS EOS with library coefficients [Thompson and Lauson, 1984; Thompson, 1990]. Tables 2 and 3 summarize EOS and strength model parameters, respectively.

RESULTS

A suite of laboratory experiments performed at the NASA AVGR reveals distinct subsurface failure morphologies following oblique hypervelocity impacts into planar PMMA targets. Impact parameters (velocity, impact angle and projectile type) were varied to better understand the failure mechanisms. In particular, we focus on approximately linear, along-trajectory failure planes (“blades”) that form for very oblique ($15\text{-}30^\circ$) impacts, which vary with impact velocity, impact angle and projectile type. The following sections detail their formation, general morphology, the effects of changing impact parameters on their appearance, and details of formation mechanism.

Timing of Formation

Time sequences of damage formation are shown in Figures 1 and 2 for aluminum and Pyrex projectiles, respectively. Directly following first contact (approx 1-2 μsec), a region of voids forms underneath the impact point. Following this, an asymmetric shock wave begins to propagate outward from the impact point, directed downrange [e.g., Dahl and Schultz 2001]. Behind the shock wave, a hollow damage zone forms, which we call the “main damage region”. This region grows downward and along the trajectory from uprange to downrange. Approximately 12-14 μsec after impact, a downrange, diving “tongue” of damage begins to form. This feature initially begins to grow at an angle following the trajectory, but it typically curves during growth so that it does not necessarily end parallel to the initial trajectory. The shock wave reaches the bottom of the block around 20 μsec after impact. For high impact velocities or higher impact angles (i.e., $\geq 30^\circ$), this reflection results in a region of tensile failure at the base of the block. Between 30-40 μsec after impact (dependent on impact velocity), the damage zones are finished growing. The right-hand column of Figures 1 and 2, showing the along-trajectory failure, reveals “spiky” features protruding from the main damage zone. These represent failure planes that extend along the trajectory axis. The along-trajectory failure planes (“blades”) begin to form ~ 18 μsec after impact and are finished forming by ~ 26 μsec . This is well before the shock wave reaches, and reflects from, the surface at the bottom of the block. These planes are seen in experiments into thicker blocks as well, where no tensile failure at the base is seen due to the weakening of the shock wave with distance.

The sequence described above occurs for all impacts into unmodified planar PMMA targets. Small differences in timing depend on impact velocity and angle, but the overall morphology is similar. Increasingly oblique impact angles ($<30^\circ$) result in smaller overall damage regions and no tensile failure at the base of the block (consistent with reduced peak pressures). For very oblique impacts (15°), these blades are prevalent following impacts by hypervelocity aluminum projectiles. The blades are less well defined for Pyrex or PMMA projectiles. As discussed below, higher impact angles also produces blades, but they are less numerous and with a different form.

CTH model results with identical conditions to the laboratory experiments provide insight into the timing of growth as well as evolution of these blade-like features, which appear to begin growing beneath the impact point and evolve downrange (Figure 3 and 4). The two planes shown in Figure 3 are at $x = 0$ cm (the plane perpendicular to the trajectory at the impact point) and $x = 2$ cm downrange (near the crater center). The magnitude of the shear stress following impact (Figure 4) reveals that the maximum shear stresses beneath the crater exceed conditions for failure (shown as green). The blade-like features initially form below the impact point and evolve downrange underneath the crater center after ~ 12 μsec . Similar time evolution is seen in laboratory experiments.

Morphology

The blades generated in laboratory experiments form failure planes roughly aligned with the trajectory. Blades are best expressed with aluminum projectiles and form as concentrated sets, while Pyrex or PMMA projectiles result in a more distributed set of failure planes. From an UR (uprange) viewpoint, the blades extend radially out from the

hollow, main damage zone, below the impact point (Figure 5). In some cases, several sets of blade-like features can be identified and are classified as “major” and “minor”, with minor blades occurring between major blades.

Mode of Failure/Growth Rate

Propagation velocities of isolated cracks help to distinguish between failure modes. The three types of cracks (Mode I, II and III) have distinctive crack speeds (values shown in Table 4 for PMMA). Mode I cracks (extension cracks) are limited by the Rayleigh wave speed, c_R . Mode II (shear cracks) cracks are limited by the sound speed of the material c_p , whereas Mode III cracks (shear cracks) are limited by the shear wave velocity in the material, c_s . The observed damage growth for a 0.635-cm projectile impacting into a planar PMMA target at 4.44 km/s at an angle of 30° (Figure 6) depends on azimuth (inset, Figure 6). The slopes represent the growth rate of the damage region. Two different slopes are highlighted: directly below the impact point, and following the trajectory in the downrange direction. These slopes indicate growth rates faster than c_s but slower than c_p . Similar results were seen for a range of impact velocities in Stickle and Schultz [2011].

A comparison between experimental results and corresponding numerical simulations reveals further details about failure mode (Figure 7). Note the presence of blade-like features beneath the main damage region in the experiment and the corresponding CTH models. 3D CTH models demonstrate that the main damage region correlates with conditions of shear failure, rather than purely extension. The mesh was seeded with Lagrangian tracer particles, originally in horizontal lines through the target,

in order to track material motion. Views of the main damage region illustrate how the material shears along the blade-like features (Figure 8).

Angle and Projectile Effects

Impacts with equivalent kinetic energy (but different projectile types) show marked differences in morphology of the subsurface damage (Figure 9). Both impacts were at an angle of 30°: one with an aluminum projectile (right), the other, a Pyrex projectile (left). Because the kinetic energy is the same, observed differences in morphology are assumed to be due to other processes. Here, the overall damage extent is the same for both impacts. The final morphology of the damage structure is distinct, however. The aluminum projectile results in distinct failure planes along the trajectory, whereas the Pyrex projectile generated a distributed, “feathered” pattern.

These morphology differences also occur clearly when the damage is examined from below (Figure 10). All three experiments shown are for 30° impacts. Impacts with Pyrex and aluminum projectiles (Figure 10A and 10C, respectively) result in along-trajectory failure planes. The planes are more pronounced and distinct from one another in the case of an aluminum projectile. A PMMA projectile, however, results in very different subsurface morphology (Figure 10B). Instead of linear, sub-parallel, along-trajectory damage planes, the fractures curve, and the primary damage region is made up of arcuate failure planes that make concentric, sub-circular patterns.

For experiments with aluminum and Pyrex projectiles, the number of blades can be counted. Care must be taken, however, because in some cases, especially with Pyrex projectiles, the primary damage region is composed of a more “distributed” pattern of

failure planes (e.g., Figure 9). In these cases, the most prominent along-trajectory planes were counted, and shorter, weakly developed features were not considered. The number of blades was counted for a range of impact velocities at impact angles of 15-30° (Figure 11). Above 30°, these features are not clearly identifiable, and the primary region is comprised of concentric, sub-circular failure planes (Figure 12).

Fracture Plane Textures

The damaged target for a 15° impact of a 0.635-cm aluminum projectile at 3.89 km/s was cut into two pieces parallel to the trajectory, bisecting the main damage zone (Figure 13). The left-hand and right-hand sides of the cut target were polished and then photographed to record the texture of the failure planes. This experiment reveals four main subsurface damage zones: the area directly beneath the impact point, a hazy region uprange of and below the impact point composed of a cross-hatch pattern of small cracks (Figure 14D), the downrange, diving feature (Figure 14C), and the blade-like failure planes below the impact point extending downrange (Figure 14B). A hollow zone separates the initial damage zone from the blades here and in most other experiments. Target geometry and impact angle can affect this morphology: the damage structures are slightly different for layered targets or for high angle impacts ($\theta > 45\text{-}60^\circ$), when the damage patterns become increasingly symmetric. Impacts into layered targets (Plasticine overlying the PMMA surface), for example, result in the main damage zone of blades that does not close on the uprange side (Figure 15, compare to Figure 10 for unlayered targets).

Under magnification, each of the three main (well-developed) regions of damage exhibit distinct textures on the failure planes. The downrange, diving feature has a stepped-like appearance (Figure 14C) along the main failure planes and a mottled surface texture (Figure 16). Some experiments also exhibited a set of parallel fracture planes along the lateral edge of this feature (Figure 17). In detail, the planes below (and to either side of) the impact exhibit conic patterns on the fracture surface, with small, irregularly shaped opaque regions separated by linear, nearly transparent boundaries (noted by white arrows in Figures 14B and 18). The mottled surface texture does not depend on projectile type or impact angle ($15\text{-}30^\circ$), as shown in Figures 14B and Figure 18; the inset in Figure 14B shows some of these boundaries outlined for reference. While they extend along the trajectory, the blades are composed of smaller, interconnected cracks (Figure 18, black arrows). Figure 14D highlights two views of the cross-hatch damage. While identifiable in targets impacted at 30° , this type of damage is best expressed at 15° . At higher impact angles, this region is either not present, or hidden within hollow damage regions. Darkened regions are seen along some of these along-trajectory failure planes for impacts into PMMA targets overlain by a Plasticine layer (Figure 19).

DISCUSSION

The oblique-impact experiments illustrate the formation of three main damage regions, each with distinct textures. Along-trajectory, blade-like failure planes grow rapidly with respect to the acoustic velocities of the target material for both aluminum and Pyrex projectiles and become increasingly pronounced as impact angle decreases.

Here, we discuss these observations and their implications for failure mode of the target material, with ramifications for large-scale planetary observations.

Results of CTH simulations indicate that the observed blade-like features are caused by shear failure (Figs. 4,7,8). This is also revealed in laboratory experiments, where darkened regions occur along the surface of some of the blades (Fig. 19). These darkened regions are likely carbonized areas along the fracture planes. Carbonization in PMMA is the result of chemical decomposition that occurs at temperatures around 250°C [Yamasaki *et al.*, 2000], which may result from frictional sliding along the failure planes. Previous experimental work has shown that significant heating is seen following shear deformation experiments in PMMA [Bjerke and Lambros, 2002]. Texturally, the blade-like planes are also different than other regions in the subsurface (Figs. 15-18). Purely extensional regions have a very different texture than the failure planes, thereby indicating a different failure mechanism. Thus the “blades” are interpreted to be a result of purely shear processes or due to mixed-mode failure.

Computations reveal that blade-like planes grow rapidly from the point of impact to downrange (Figure 4), similar to observations in the laboratory experiments (Figs. 1 and 2). The blades form directly beneath the impact point about 8 μ sec after impact in the matched CTH models, sooner than their appearance in the experiments. This contrast in initiation results from the finite time for crack initiation and growth in the experiments, a process not incorporated into the CTH model.

Two other processes also contribute to the difference between the numerical model and experiments. First, the continued momentum from a highly oblique impact does not instantly transfer its momentum; rather, projectile penetration (and failure) continuously

contributes to the growth of these damage planes downrange. Second, the rate of growth of these damage planes may be an indication of failure mode. Isolated shear-mode cracks tend to grow between the shear wave velocity (c_s) and the sound speed (c_p) of the material, whereas tensile cracks are limited by the Rayleigh wave speed (c_R) [e.g., Ravi-Chandar *et al.*, 2000]. While crack interactions within damage zones are not fully understood, the rates of damage growth for the blades (Figure 6) are faster than c_s but slower than c_p . Consequently, the observed crack growth in the experiments is consistent with damage region composed of shear cracks. Strassburger *et al.* [2008] reached similar conclusions for damage growth in transparent materials and noted that correlation of damage growth rate with shear deformation information from numerical models can help explain damage development in experimental targets. Here, the rapid rate of damage growth, coupled with the CTH results (showing failure by shear deformation) indicates that shear failure is responsible for the blade-like failure features. Further, at high rates, and under shear conditions, PMMA is known to form adiabatic shear bands and frictional melting along the fracture surfaces [Rittel and Brill, 2008]. Thus, frictional melting might also be expected for the blades in these experiments.

Textures of the damage planes in the laboratory experiments (Figures 14, 16 and 18) also help to characterize the failure process. Experimental work on failure mechanisms in polymers [e.g., Deblieck *et al.*, 2011] shows that brittle polymers (such as PMMA at high rates) will fail in discrete fractures when the material undergoes plastic yielding after shear deformation. Fractographic analysis of failure in PMMA also indicates that spallation (or purely extensional failure) results in mirror surfaces and hackles on the failure planes. In contrast, ductile shear failure resulted in failure planes comprised of

elongated dimples with signs of softening and melting [Rittel and Brill, 2008], sometimes described as “multi-faceted” [Williams *et al.*, 1983]. Hackles and mirror surfaces are seen in regions of the experiments undergoing spallation and in flares at the edge of some fracture planes (e.g., Figure 18A). The blades and diving tongue, however, exhibit a mottled texture more characteristic of shear failure. Future work examining these planes at even higher magnification will allow more detailed comparisons to the melting and softening results of Rittel and Brill [2008].

For impacts with equivalent impact energy, the style of projectile failure can affect subsurface damage morphology and structures. In general, aluminum projectiles result in fewer, but more pronounced, blade-like features, which contrast with smaller and more numerous features from Pyrex or PMMA projectiles (Figure 11). Pyrex projectiles generally result in a more “distributed” main damage region, with damage planes that are not as clearly defined. In contrast, the aluminum projectiles result in discrete, blade-like features. Sometimes, these planes are interspersed with distributed-like failure, and we can classify “major” and “minor” blades. In other cases (such as is shown in Figure 9B), the blades occur without interspersed feathering. The damage resulting from the PMMA projectile (Figure 10B) is much more symmetric, with damage planes curving into a more circular pattern. These contrasting patterns likely reflect contrasting projectile-failure styles. PMMA projectiles may melt and vaporize, which results in sudden coupling like a point-source. In contrast, Pyrex will catastrophically disrupt upon impact, which should result in a greater number of smaller blades as the pieces continue to impact along the trajectory. An aluminum projectile will continue to penetrate the target as it moves

downrange without shattering, or decapitate and then re-impact downrange [e.g., Gault and Wedekind 1978; Schultz and Gault 1990].

Along with projectile type, impact angle plays a significant role in the formation of the blades. Increasingly oblique impacts accentuate the formation of the blade-like failure planes, while higher angle impacts inhibit their formation. Impacts nearer to vertical (45-90°) result in more concentric, or cone-shaped, failure patterns (Figure 12), similar to the failure patterns seen for PMMA projectiles (Figure 10B). In contrast to highly oblique impacts, high-angle impacts couple energy to the target near the impact point, thus behaving more as a point-source.

Implications

The term “pseudotachylyte” was first used by Shand [1916] to describe dense, black-colored rocks at the Vredefort impact structure. Since then, pseudotachylytes have been defined as rocks resulting from frictional melting on a slip plane, which may include unmelted, lithic clasts or high-pressure mineral polymorphs [Spray, 2010]. This rock type may be tectonically produced [e.g., Sibson, 1975; Swanson, 1988] or formed by hypervelocity impact [Lambert, 1977; Reimold, 1995; Spray and Thompson, 1995; Thompson and Spray, 1996; Spray 2010]. Throughout the impact literature, “pseudotachylyte” is often broadly classified into two main groups [Lambert, 1981; Martini, 1991; Spray, 1998]: those that form early in the crater process (during the contact and compression stage), and those that form after pressure release. Reimold [1995, 2005] challenges these classifications, suggesting that anything not clearly identified as a pseudotachylyte (which is defined as a frictional melt) be referred to as

“pseudotachlytic-like” or “pseudotachylitic breccia”. For the purposes of this study, we adopt the nomenclature of Spray [1998], where impact-induced pseudotachylytes are broadly characterized into two main groups: S-type, which form during the contact and compression stage of the impact event, and E-type, which formed during the modification stage. S-type pseudotachylytes are derived from a combination of friction and shock processes, as melting will occur during shock loading and be accompanied by frictional heating along micro slip zones [Spray, 2010]. While field observations indicate an impact-related process, specific mechanisms for generating pseudotachylytes have remained in debate [e.g., Melosh, 2005; Riller, 2010].

Veins of pseudotachylytes are found in the central peaks of some terrestrial craters (e.g., Dressler and Reimold, 2004, Manicouagan [Dence, 1964; Dence, 1965; Floran and Dence, 1976], Rochechaurt [Lambert, 1977], Vredefort [Reimold and Gibson, 2005]), as well as in mare samples from the moon [Reimold, 1995]. These pseudotachylytes are often small in size (width) and likely form during the impact event (making them S-type pseudotachylytes as described by Spray [1998]) rather than later by modification. Further, S-type pseudotachylytes tend to be found within the inner-most shock zone and distributed in a random way [Spray, 1998]. We suggest that these experiments, and the resulting frictional, blade-like failure planes may provide a mechanism for pseudotachylyte formation within central peaks. Melosh [2005] theoretically showed that strain rates and stresses within large impact craters would plausibly create mm- to cm-wise shear zones lined with frictional melt. Our experiments add to this, indicating that frictional melting may occur in the subsurface along failure planes paralleling the impact trajectory. Pseudotachylytes within exposed central peaks are typically jumbled

following the modification process [e.g., Howard *et al.*, 1972; Lambert, 1981; Osinski and Spray, 2001]. During uplift of the central peaks, the along-trajectory planes will further deform and result in a random orientation and location for pseudotachylytes within the central peak structures.

While eroded impact craters on Earth reveal the three-dimensional view and processes occurring at meter scales (e.g., pseudotachylytes), planetary surfaces retain their original structure. Although pseudotachylytes are not recognized, certain structural elements within the central peaks of oblique impacts are highly suggestive. Central peaks in general have been interpreted as expressions of inward flow due to gravity collapse [e.g., Dence *et al.*, 1968; Gault *et al.*, 1968; Hale and Head, 1979; Melosh, 1981] or upward displacement due to dynamic rebound [e.g., Roddy, 1977; Milton and Roddy, 1972; Pike, 1980; Schultz, 1992].

The appearance of central peaks in oblique impacts provides one strategy to assess the relative role of collapse and uplift [Schultz, 1988; Schultz, 1992; Kenkmann *et al.*, 2005]. Impact trajectories can be identified through asymmetries in the distribution of the ejecta deposits [e.g., Gault and Wedekind, 1978; Herrick and Forsberg-Taylor, 2003; Anderson *et al.*, 2004; Herrick and Hessen 2006]. At very low impact angles, however, crater shape in plan and morphology provide an equally compelling case [e.g., Gault and Wedekind, 1978; Schultz and Lutz-Garihan, 1982; Schultz, 1992; Burchell and Whitehorn, 2003]. One identifiable structural element is a central ridge that characterizes highly oblique impacts (Figure 20). Linear central peak complexes have been previously recognized with some examples attributed to structural control [Allen, 1975; Hale and Head, 1979]. Hale and Head [1979] conclude that central peak geometry is controlled by

substrate properties rather than impact angle because many linear peaks roughly align with the so-called “lunar grid” [Fielder, 1967]. In highly oblique impacts, however, the linear peak parallels the trajectory inferred from other evidence including the surrounding butterfly ejecta pattern and structural elements including oblong crater shape and rim height variations [e.g., Schultz and Lutz-Garihan, 1982]. In this case, the linear central ridge occurs without evidence for significant inward collapse. For example, the central ridge in Buys-Ballot occurs where evidence of wall failure is minimal (Figure 20). This observation suggests that the central ridge may be controlled by crater formation.

Higher angle oblique impacts (revealed by ejecta asymmetries) also exhibit linear elements. King crater, on the lunar farside, exhibits a distinct breached and elongate central peak structure (Figure 21). The crater Tycho exhibits a similar (but more subtle) linear central massif assemblage. In both cases, the linear pattern follows the trajectory inferred from the asymmetric pattern of ejecta [e.g., Schultz and Anderson, 1996]. The large amount of slumping and inferred inward collapse, however, hides the evidence revealed in Figure 20 and complicates any interpretation based on primary structural control.

We propose that linear central peaks may be the result of subsurface failure planes following the impact that mimic the trajectory [e.g., Schultz, 1992]. Such planes may set up zones of weakness along the trajectory that are then reactivated as the rocks rebound during central peak formation. These, then, will form elongated central peaks. Failure planes within our experiments, which form roughly parallel to the impact trajectory, may provide a small-scale example of this process, expressed at large scales by linear central peak structures within highly-oblique craters on planetary surfaces. Pseudotachylytes

formed along these planes during the impact could either direct the uplift along the original trajectory or could become folded and faulted during central peak uplift, thereby jumbling the initial pattern.

At larger scales, the discrete failure planes seen in the experiments also may provide clues for a mechanism to weaken rocks enough to allow modification at small values of stress. Spray [1998] suggests that S-type pseudotachylytes may provide a mechanism to facilitate hydrodynamic behavior within the innermost zone of an evolving crater. Melosh [2005] estimates that an ~ 3 MPa strength is necessary to facilitate crater collapse and central peak formation, which is significantly weaker than the actual strength of rock. Adopting the interpretation of Spray [1998], S-type pseudotachylytes might provide this weakening, thus these planes may represent an additional way to “weaken” the rock. Fractured rocks, especially with areas of melt along fracture faces, are weaker than solid blocks, and so pre-existing faults may aid in the uplift process [see also discussions by Fiske *et al.*, 1995, Lana *et al.*, 2004 and Kenkmann *et al.*, 2000]. Numerical simulations by Collins *et al.* [2004] illustrate that rocks near the center of an impact crater will experience double the amount of net plastic strain compared to the maximum total strain. This is a result of the shear direction being reversed during crater growth and collapse, which results in greater amounts of plastic shear strain within the target. Thus, large amounts of shear strain may cause melt to form regardless of the sense of shear, increasing the weakening of these shear zones.

CONCLUSION

A suite of laboratory experiments using PMMA targets reveals subsurface damage planes parallel to the trajectory (“blades”) for highly oblique impacts (15-30°). Projectile failure plays a role in the development of these blades: aluminum projectiles result in distinct along-trajectory blades for both 15° and 30° impacts, whereas the blades are more weakly developed for Pyrex projectiles and non-existent for PMMA projectile. The blades are characterized by surface textures that are unique relative to other failure regions. The observed growth rate of the blades exceeds the shear wave speed of PMMA. Coupled with CTH calculations, these observations indicate that the blades are the result of shear deformation and localization. The blades grow from the point of impact downrange and reflect the continued momentum transfer into the target that becomes increasingly distinct with decreasing impact angle. These discrete shear failure planes may be a mechanism for formation of S-type pseudotachylytes found in large-scale impact craters. Frictional melting occurs along failure planes paralleling the impact trajectory early in the crater process, which are then exposed as central peaks are uplifted.

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TABLES

Table 1. Experiments used in this study

Shot number	Projectile	Speed [km/s]	Angle [deg]	Special Target Conditions
090627	0.635-cm Pyrex	3.58	30	
090620	0.635-cm Pyrex	4.42	30	
090619	0.635-cm Pyrex	5.02	30	
090622	0.635-cm Pyrex	5.15	30	
090618	0.635-cm Pyrex	5.21	30	
090613	0.635-cm Pyrex	6.43	30	
090615	0.635-cm PMMA	5.43	30	
090626	0.635-cm aluminum	3.87	30	
090614	0.635-cm aluminum	4.88	30	
090612	0.635-cm aluminum	5.5	30	
090617	0.635-cm aluminum	5.6	30	3/16" Plasticine layer on the surface
090616	0.635-cm aluminum	5.92	30	
100623	0.635-cm Pyrex	4.91	15	
100622	0.635-cm Pyrex	5.04	15	
100621	0.635-cm Pyrex	5.19	15	
100625	0.635-cm aluminum	3.62	15	
100628	0.635-cm aluminum	3.66	15	
100630	0.635-cm aluminum	3.77	15	
100631	0.635-cm aluminum	3.89	15	

100629	0.635-cm aluminum	4.86	15	
100633	0.635-cm aluminum	4.74	15	1/16" downrange shelf filled with Plasticine
100632	0.635-cm aluminum	4.78	15	1/8" downrange shelf filled with Plasticine
100703	0.635-cm aluminum	5.2	15	1/8" downrange shelf filled with Plasticine

Table 2. EOS parameters for materials used in small-scale CTH simulations

	Pyrex¹	Styrofoam^{1,2}	Aluminum	PMMA^{1,2}
Density (g/cc)	2.23	0.035	2.7	1.186
Sound speed (km/s)	2x105	2.74	5.38	2.3
Mie-Gruneiesen: S1	1.5	1.319	--	1.75
Mie-Grüneisen : S2	0	0	--	-0.13
Gruneisen Parameter: Γ	1	1.18	2.1	0.91
Cv (erg/g/eV)	1x10 ¹¹	1.34x10 ¹¹	1.02x10 ¹¹	3.5x10 ¹¹

¹Marsh (1980); ²Van Thiel (1977)

Table 3. Strength parameters for materials used in small-scale CTH simulations

	Styrofoam	Plasticine^{1,2}	Pyrex	Aluminum³	PMMA
Yield (MPa)	0.50	0.05	1000	276	120
Poisson	0.25	0.44	0.26	0.33	0.37

¹Christensen et al. 1968; ²Austin et al. 1980; ³Library parameters for Aluminum 2024 in the Johnson-Cook material strength model

Table 4. Limiting velocities for three crack types in PMMA

	Velocity [m/s]	Limits
Sound Speed c_p	2700 ¹	Mode II, shear cracks
Shear wave velocity c_s	1050-1100 ²	Mode III, shear cracks
Rayleigh wave speed c_R	950 ³	Mode I, extensional cracks

¹Carlson *et al.*, 2003; Babin *et al.*, 2004; ²Harding and Du, 1997; Ravi-Chandar *et al.*, 2000; ³Ravi-Chandar *et al.*, 2000

FIGURE CAPTIONS

Figure 1. Time sequence showing damage evolution for an impact of a 0.635-cm aluminum projectile at 15° and 4.87 km/s. (left) Looking from the side of the block; (right) Looking from uprange to downrange.

Figure 2. Time sequence showing damage evolution for an impact of a 0.635-cm Pyrex projectile at 15° and 4.91 km/s. (left) Looking from the side of the block; (right) Looking from uprange to downrange.

Figure 3. Schematic showing the geometry for Figure 4. Tracking evolution of failure planes along the trajectory provides insight into their timing and growth.

Figure 4. 3D CTH simulation of a 0.635-cm aluminum projectile into a planar PMMA target. Impact angle: 30° , impact velocity: 4.44 km/s. Images show a cross-section of the target block perpendicular to the trajectory at two locations: the plane of impact, and 2 cm downrange (shown in Figure 3). The magnitude of the shear stress (J2P) is plotted here; regions that have experienced shear stresses sufficient for failure directly beneath the crater are shown in green. The initial projectile size is shown for scale. A) Evolution through time at $x = 0$ (perpendicular to trajectory at impact point); B) Evolution through time at $x = 2$ cm downrange, at the crater center. Blade-like features grow from beneath the impact point towards downrange.

Figure 5. General appearance of “blades” and “distributed failure” for a 15-degree impact. The blue line shows the top of the target block and the arrow indicates the hollow central region. Figures are to the same scale. The damage evolution for these two experiments is shown in Figures 1 and 2. A) Failure following a 0.635-cm diameter Pyrex projectile impacting at 4.91 km/s. B) Failure following a 0.635-cm diameter aluminum projectile impacting at 4.87 km/s.

Figure 6. Damage growth through time at 5 different azimuths for a 0.635-cm aluminum projectile impacting into a planar PMMA target at 4.44 km/s with an impact angle of 30° above the horizontal. Distance is measured from the impact point along the side of the damage zone (left column in Figures 1 and 2). Note that the damage is growing at rates indicative of shear failure, represented by the slopes of the damage-growth curves. A time sequence of this growth and the final morphology is seen on the right in Figure 9.

Figure 7. Comparison between experimental and numerical results. Impact of a 0.635-cm aluminum projectile into a planar PMMA target. Impact angle: 30° , impact velocity: 4.44 km/s. A) Along-trajectory view of damage, 32 μ sec after impact; B) Along-trajectory view of plastic strain in 1:1 comparison CTH model, 32 μ sec after impact. Failure occurs at 10% plastic strain; C) extensional failure following the impact. The target fails in extension (dmg=1) at the base of the block due to shock wave reflection; D) Shear stress in the target 32 μ sec after impact. Regions that have experience shear stresses greater than the shear strength of the material are shown in light green.

Figure 8. CTH model showing damage at 20 μ sec after the impact of an aluminum projectile at 3.89 km/s and an angle of 15°. This image is a cross-section view, and the impact trajectory is into the page. Lagrangian tracer particles indicate movement of material, which is generally downward and outward. The inset shows that the material moves in a left-lateral shear sense across the blade.

Figure 9. Morphology of two impacts with equivalent energy. (left) 0.635-cm Pyrex projectile, impacting at 5.02 km/s at an angle of 30° above horizontal; (right) 0.635-cm aluminum projectile, impacting at 4.44 km/s at an angle of 30°. A) Time sequence, looking from uprange to downrange, showing formation and evolution of subsurface failure. B) Final damage structures. (top) looking UR to DR, (bottom) looking from the side. Note that the damage extent is the same for equivalent energy impacts, but the style is different. Aluminum projectiles result in bladed subsurface damage planes while Pyrex projectiles cause a more “distributed” failure pattern. Spiky, linear features are still seen, but they are much less pronounced than for aluminum projectiles.

Figure 10. Final damage structures for three different projectile types. All three impacts were 30° above the horizontal. The left-hand image shows the damage along the trajectory, while the right-hand image shows the damage from below. A) 0.635-cm Pyrex projectile, impact velocity: 5.02 km/s; B) 0.635-cm PMMA projectile, impact velocity: 5.43 km/s; C) 0.635-cm aluminum projectile, impact velocity 4.88 km/s.

Figure 11. Number of along-trajectory failure planes (“blades”) as a function of impact velocity for different projectile types and impact angles. A) 0.635-cm aluminum projectile; B) 0.635-cm Pyrex projectile. Blades are more well developed for 15° impacts compared to 30° impacts for both projectile types.

Figure 12. Damage patterns for high-angle impacts (45-60°). The left column shows the damage region looking from uprange (impact into the page), whereas the right column shows the damage from below. Note that along-trajectory blades are not seen; rather the damage forms a closed, circular pattern. The target surface is indicated by a white line. A) 0.476-cm Pyrex projectile, impact angle: 45°, impact velocity: 4.91 km/s; B) 0.476-cm aluminum projectile, impact angle: 45°, impact velocity: 4.3 km/s (equivalent impact energy to A); C) 0.476-cm aluminum projectile, impact angle: 60°, impact velocity: 3.85 km/s (equivalent momentum to A).

Figure 13. Viewing geometry for Figure 15. The target for a 15° impact of a 0.625-cm aluminum projectile into solid PMMA block at 3.89 km/s was cut into two pieces, bisecting the damage zone. Impact is from bottom to top. The two sides were designated “L” and “R”, for the left and right sides of the impact point when looking from uprange to downrange; the red arrow indicates impact direction.

Figure 14. Texture of main damage regions. A) Left-hand side of the cut target block (Figure 13). 15° impact of a 0.625-cm aluminum projectile into solid PMMA block at 3.89 km/s. Impact is from left to right. Approximate locations for B, C and D are outlined; B) Close up of texture on the blade fracture plane; C) Close up of the

downrange diving feature. The left-hand image (L) shows the outside surface of the failure plane, while the right-hand image (R) shows the inside surface of the failure plane; D) Close up of uprange cross hatch pattern. L and R denote views on the left and right hand sides of the cut target block.

Figure 15. Damage morphology for a layered target. Impact of a 0.635-cm aluminum projectile into a 0.47-cm thick Plasticine layer over a PMMA surface. Impact velocity: 5.6 km/s, impact angle is 30°. A) Main damage zone from below. Note that the blade-like failure planes do not arc around towards each other uprange. Impact direction is noted by the red arrow; B) Final damage from the side. The white arrows denote the cross-hatch region and the location of the blades. Plasticine layer thickness and projectile size are shown for scale. The large amount of damage at the bottom of the image is due to reflection off the bottom surface.

Figure 16. Underside focused on the downrange, diving tongue for experiment 090619. Projectile: 0.635-cm Pyrex projectile, impact angle: 30°, impact velocity: 5 km/s. The black arrow points to the mottled texture of the failure plane, while the white arrows indicate the location of the lateral, en echelon fracture planes (shown in Figure 17). Impact is from the top (red arrow).

Figure 17. Example of en echelon offset parallel fracture planes along the lateral edge of the downrange, diving feature (the region indicated by white arrows in Figure 16). Impact conditions: 0.635-cm aluminum projectile impacting at 30° and 4.8 km/s. Viewing angle is from the underside of the damage feature.

Figure 18. Close up of the blade failure planes for three different experiments, showing mottled texture with conical shaped sections (white arrows) and interconnected cracks (black arrows). A) 0.635-cm Pyrex impactor in a PMMA target at 5 km/s and an angle of 30°; B) 0.635-cm Pyrex impactor into a PMMA target at ~ 5 km/s and an angle of 15°; C) 0.635-cm aluminum projectile into a PMMA target at 5.6 km/s and an angle of 30°.

Figure 19. Close-up of failure planes, showing carbonization along the fracture-plane surface. A) Subsurface failure planes for an impact of 0.635-cm Pyrex sphere into 0.635-cm Plasticine layer over a 5-cm PMMA block. Impact angle: 15°, impact velocity: 5.7 km/s. Black rectangles show locations of B and C. B) Zoom into tip of fracture; arrows point to blackened material. C) Close-up of carbonized material along the failure plane.

Figure 20. Lunar craters resulting from highly oblique impacts. Note the oblong crater shape indicating highly oblique impact and linear central peak structures. Images are from the LROC WAC global mosaic. A) Buys-Ballot; B) Messier; C) Schiller.

Figure 21. Lunar craters resulting from oblique impacts, established by an asymmetric distribution of ejecta. These craters retained a nearly circular shape, yet their central peaks display a linear morphology. Images are from the LROC WAC global mosaic. A) King Crater; B) Tycho.

FIGURES

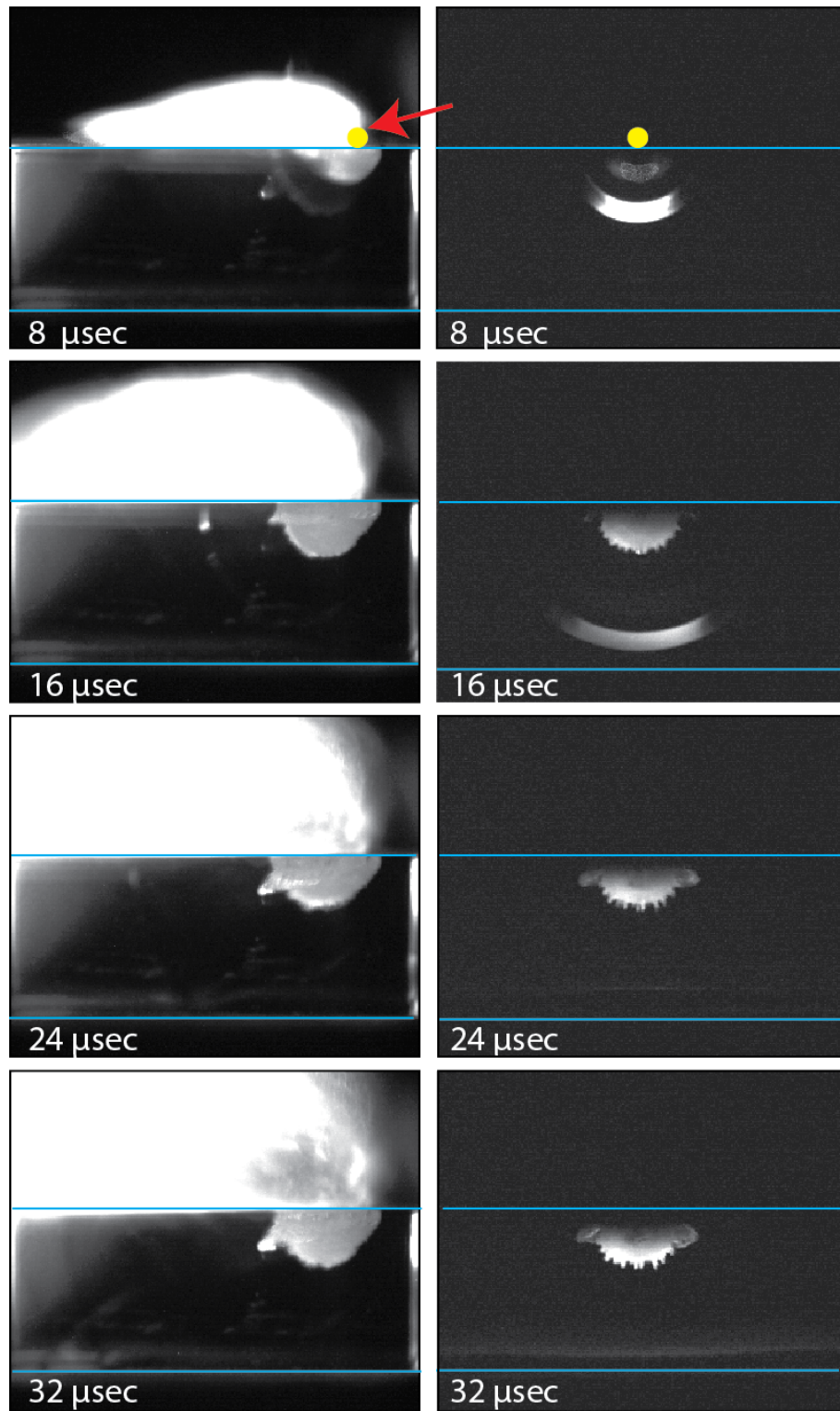


Figure 1

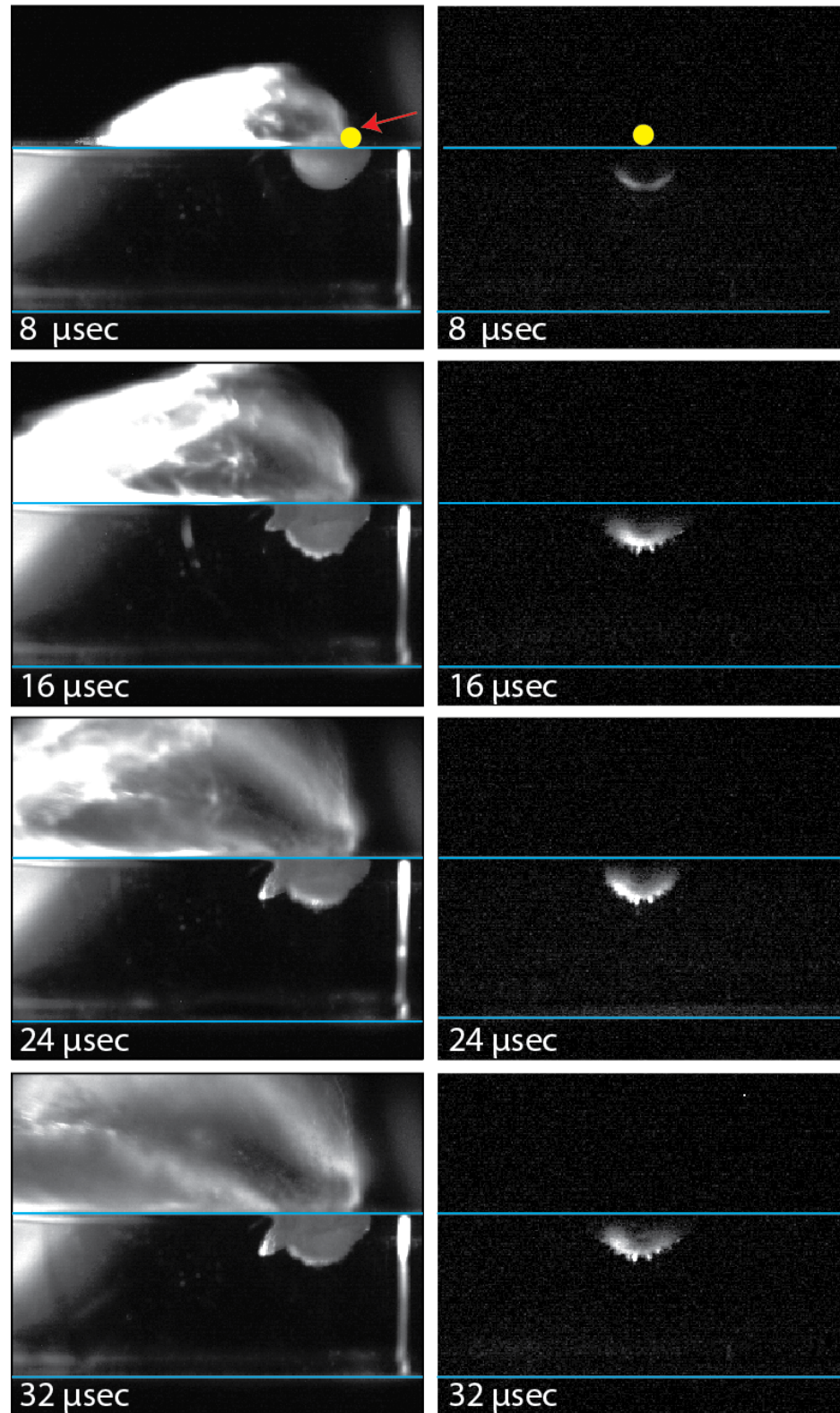


Figure 2

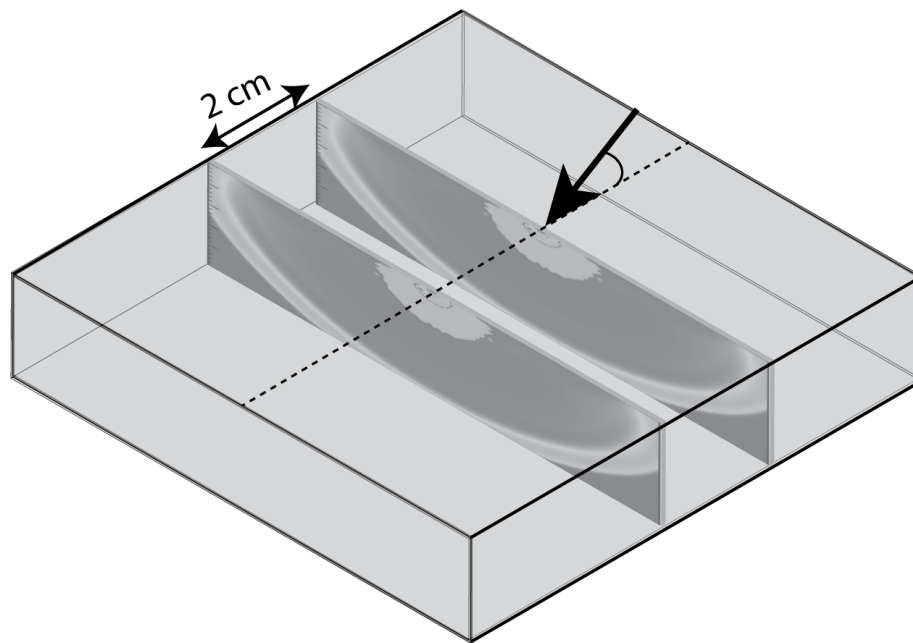


Figure 3

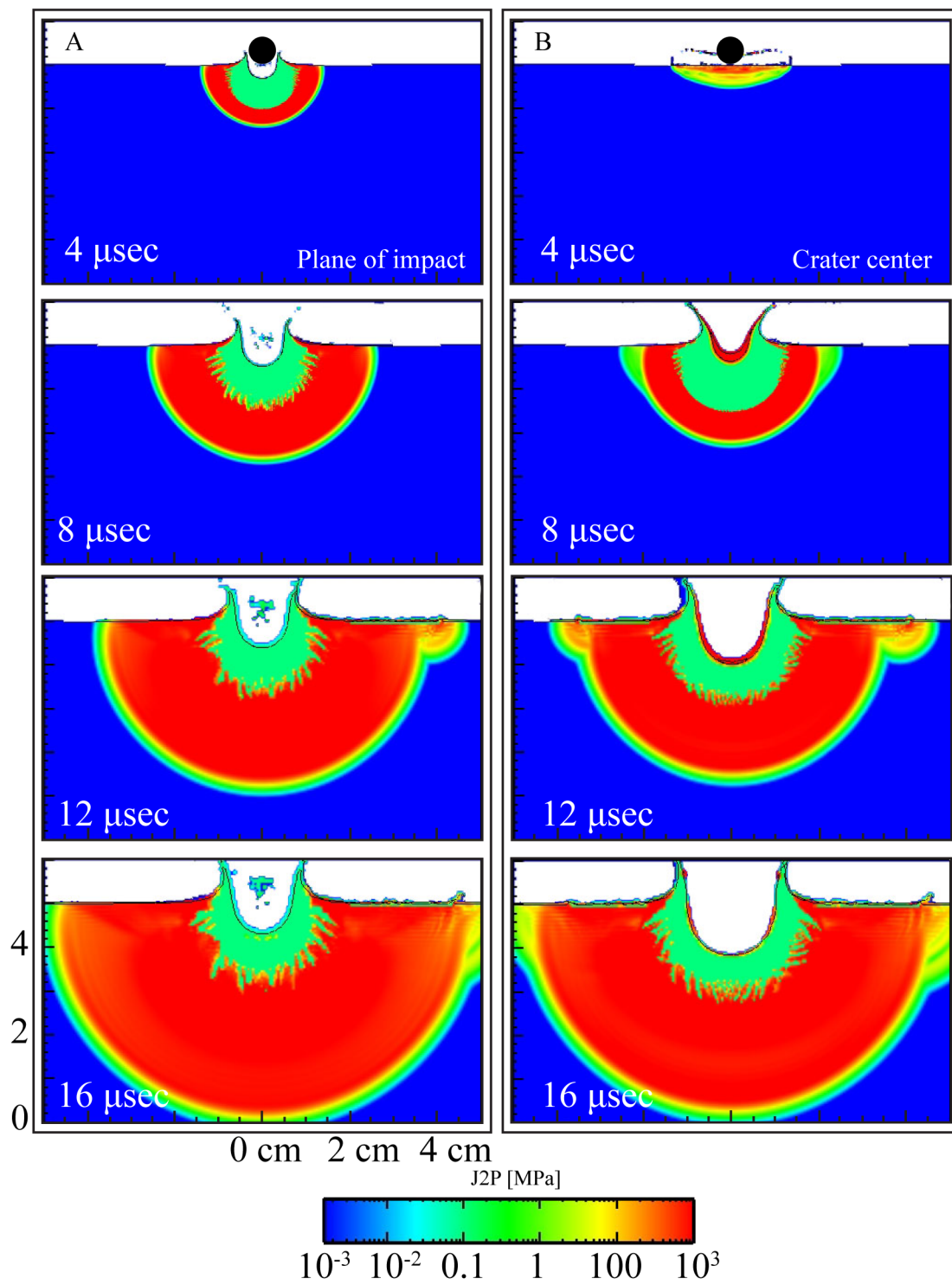


Figure 4

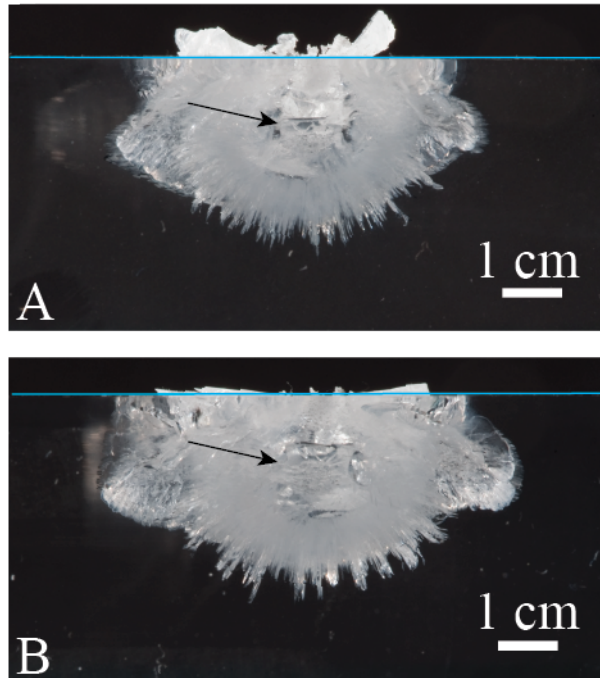


Figure 5

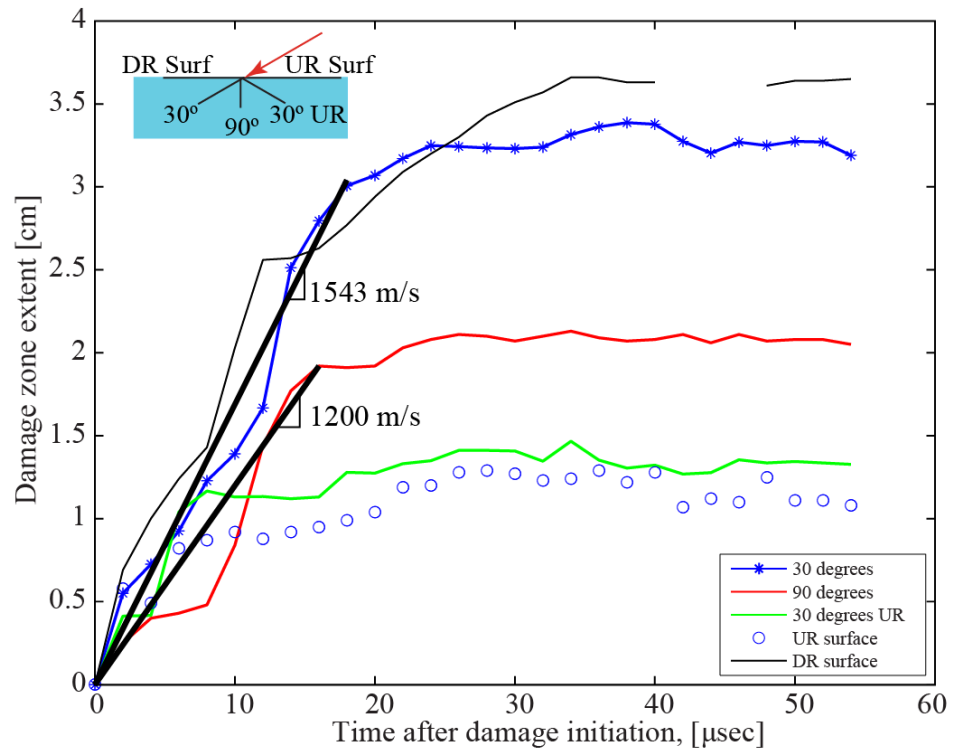


Figure 6

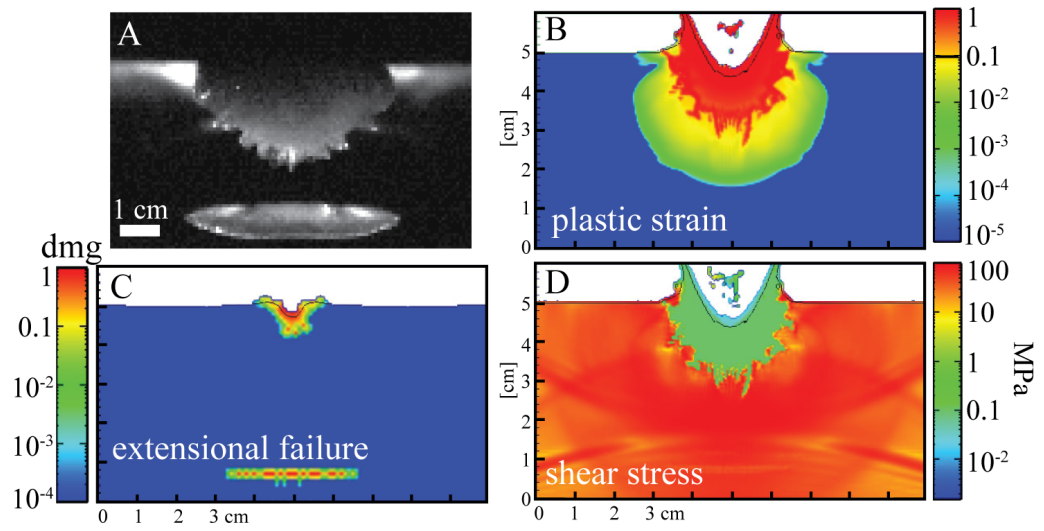


Figure 7

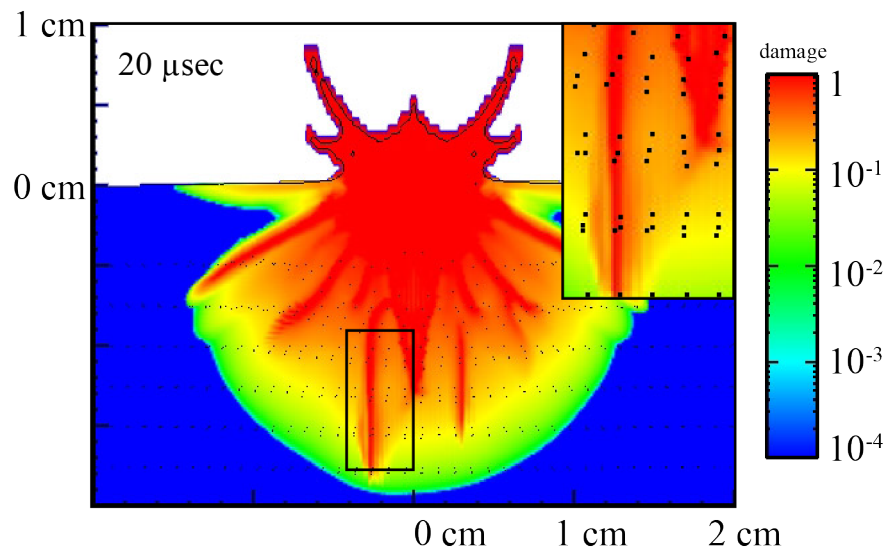


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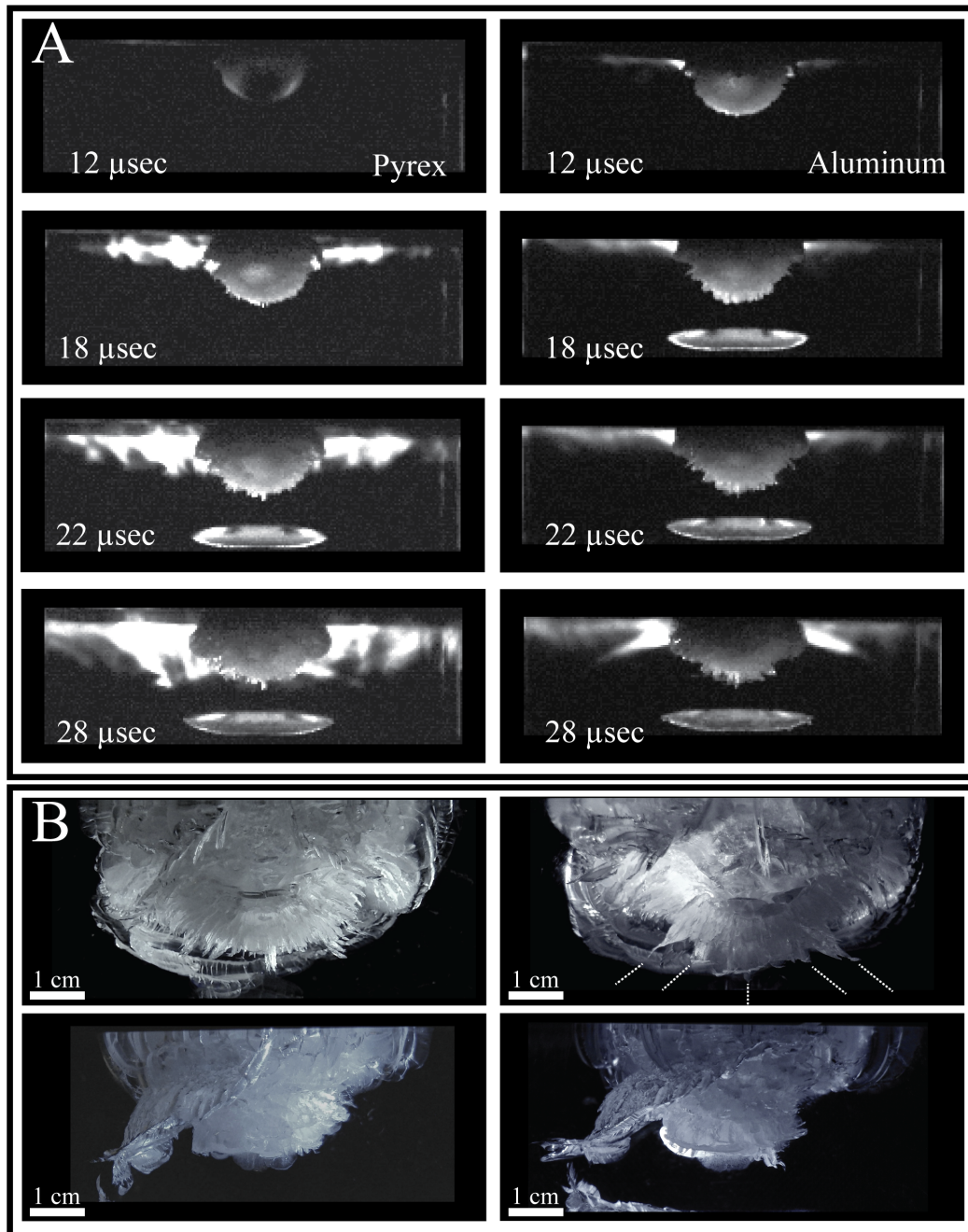


Figure 9

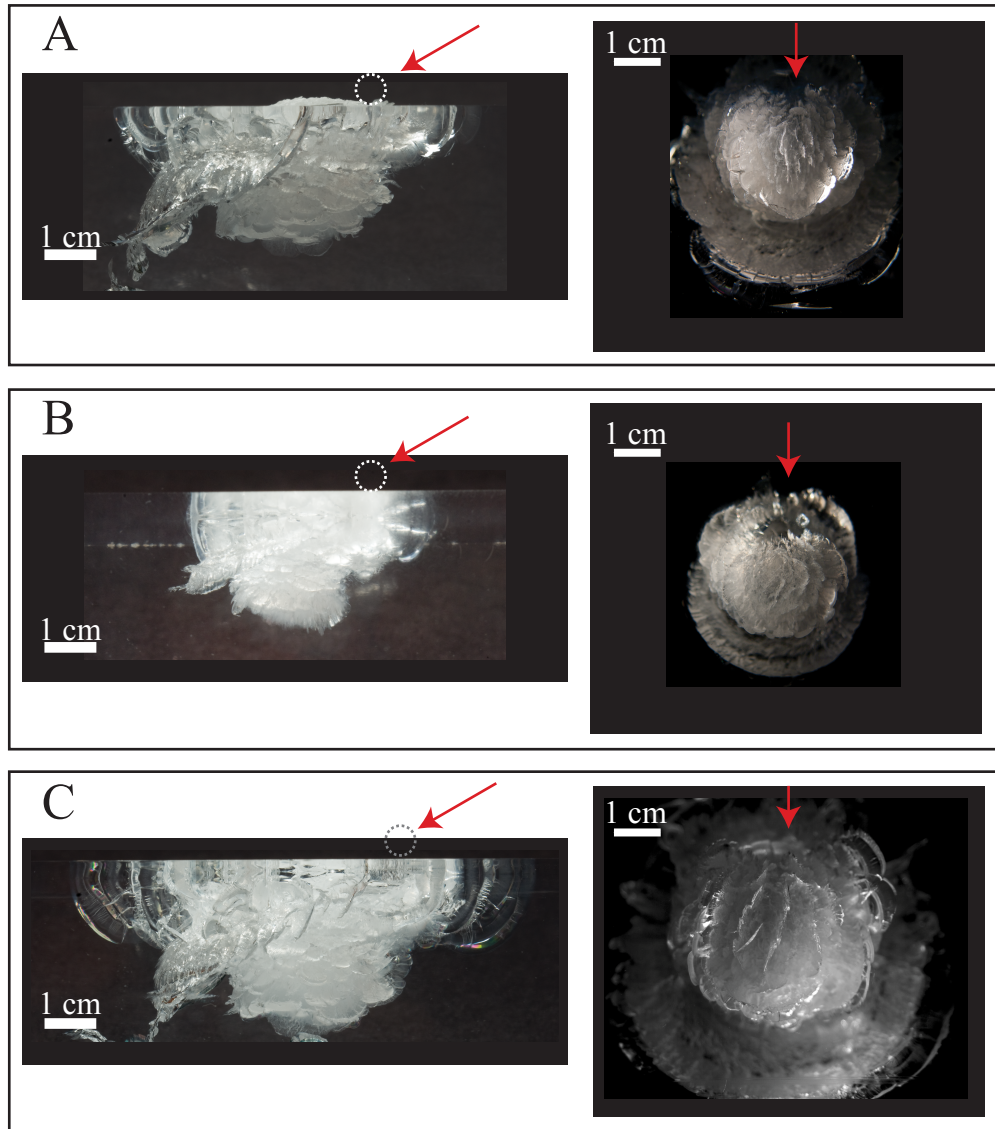


Figure 10

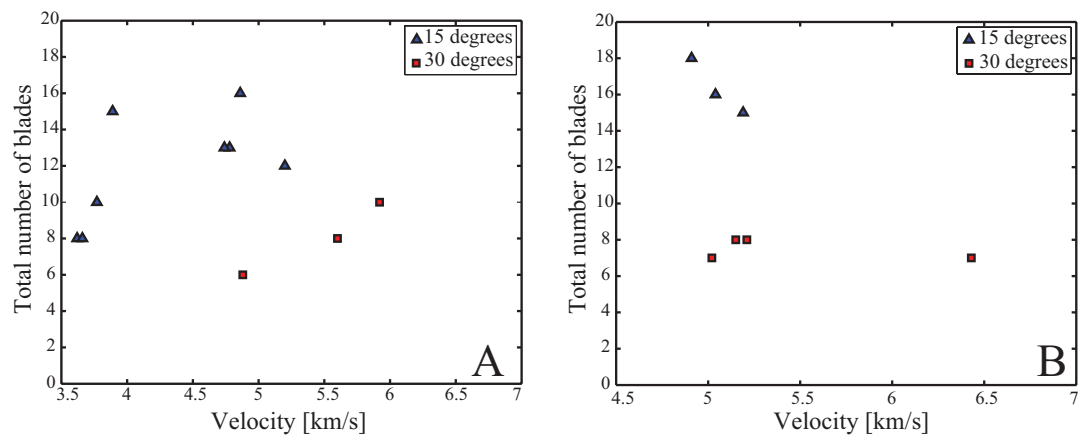


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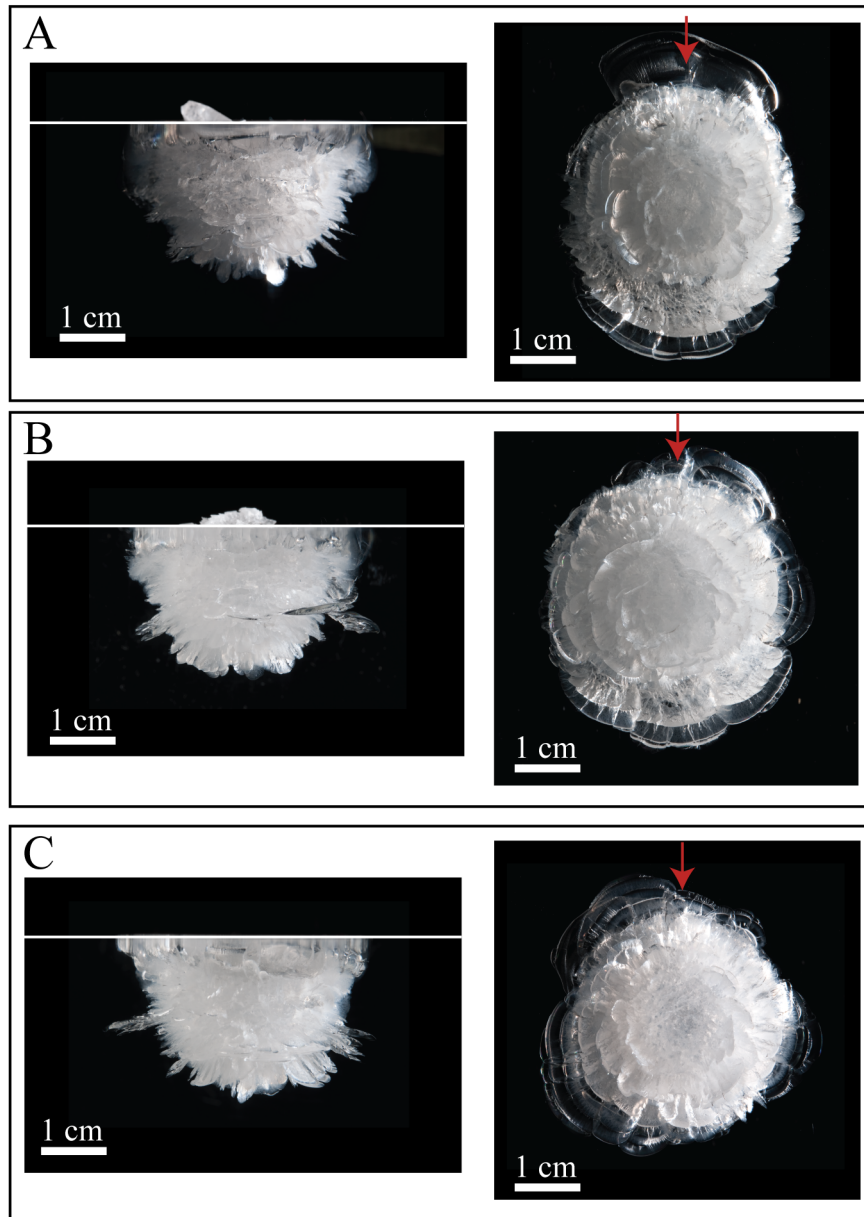


Figure 12

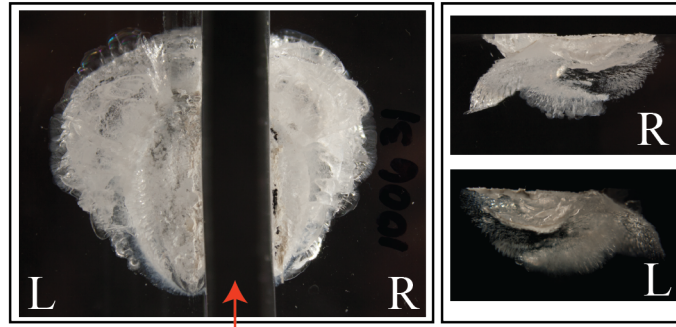


Figure 13

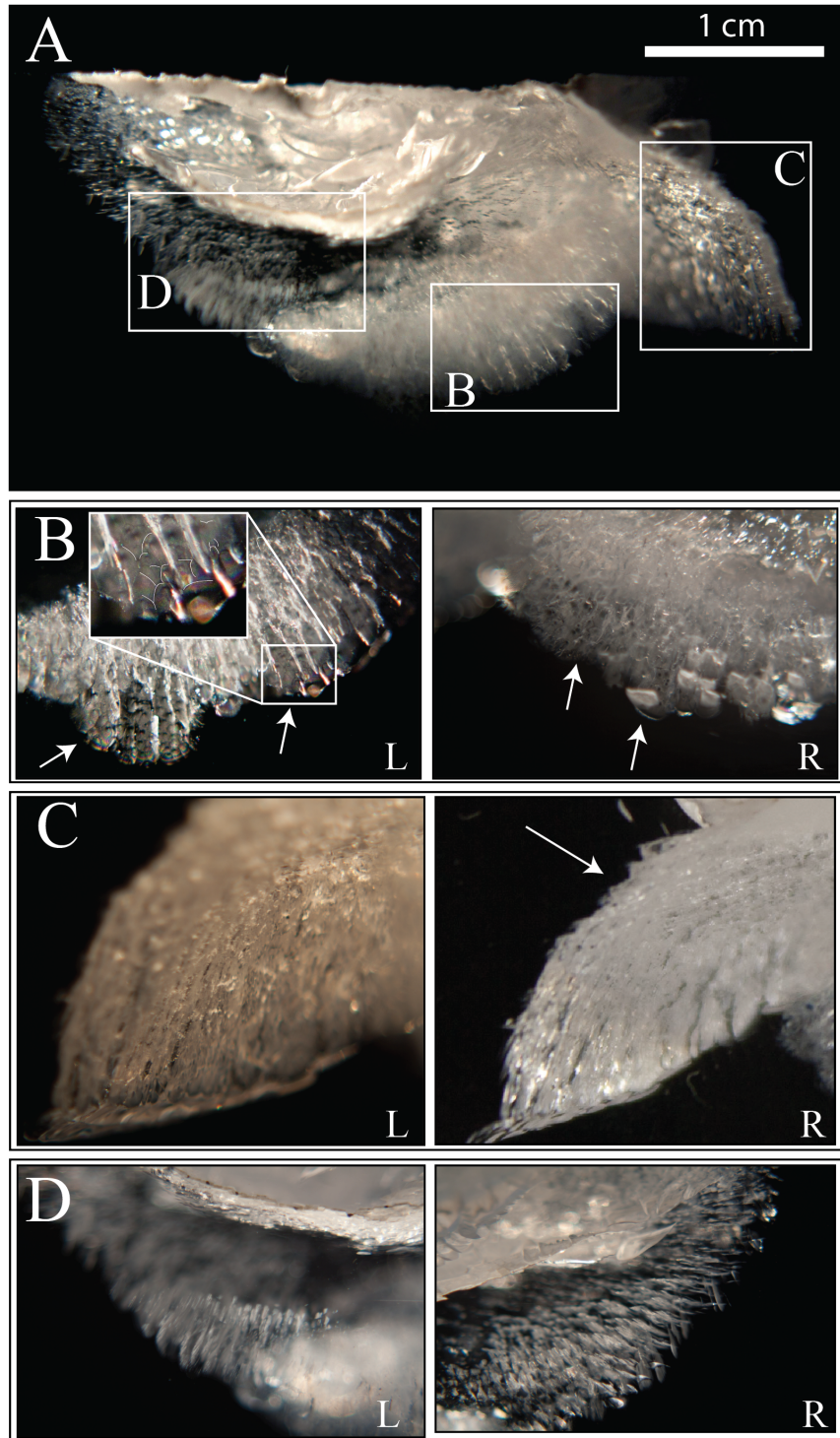


Figure 14

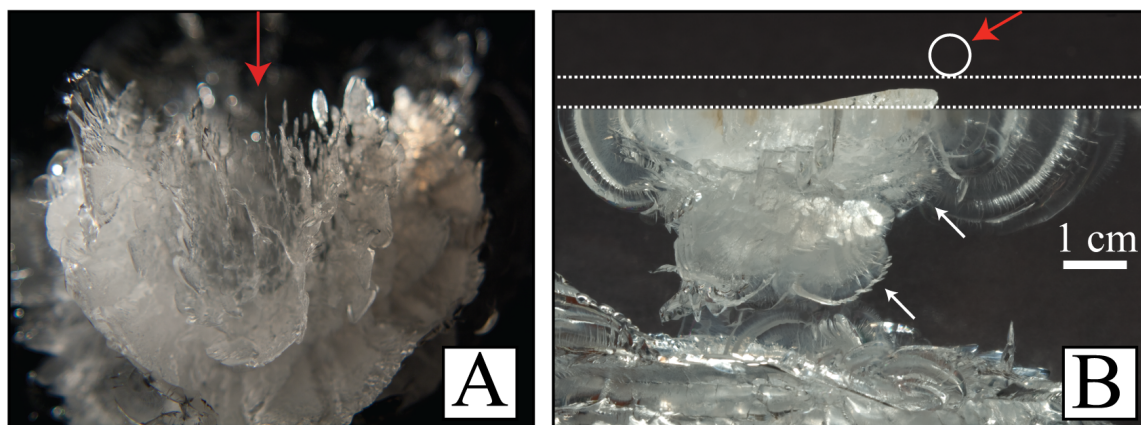


Figure 15

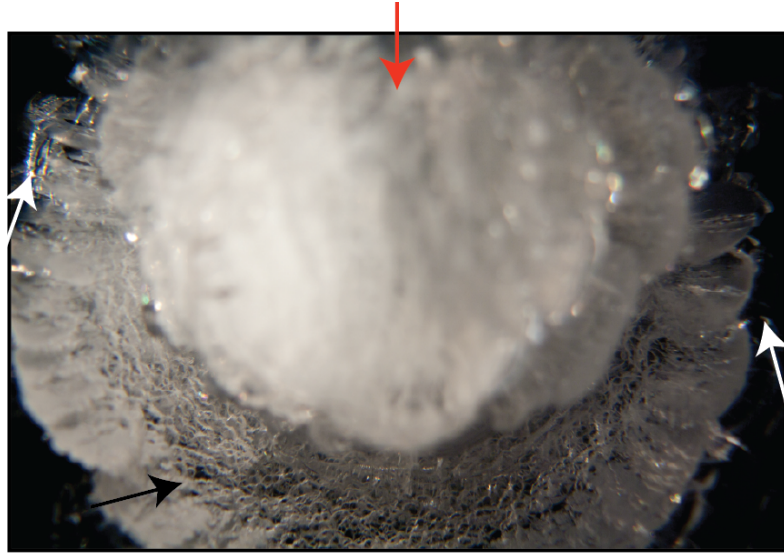


Figure 16

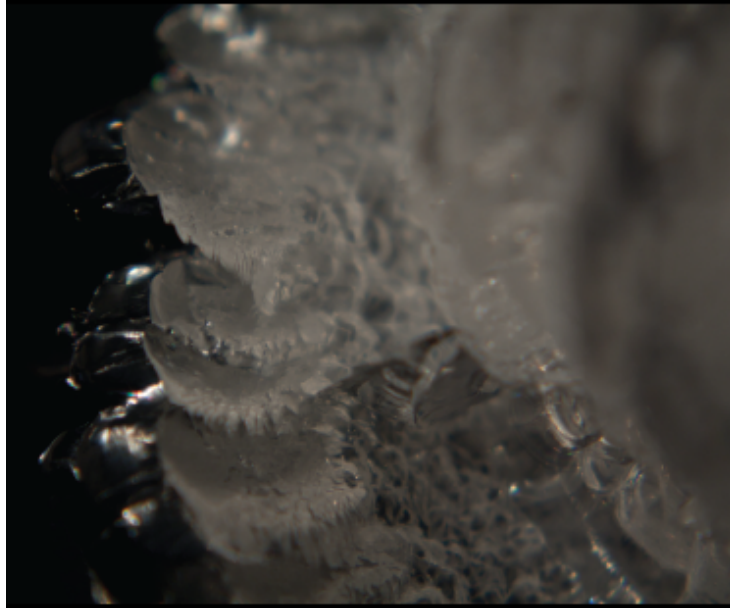


Figure 17

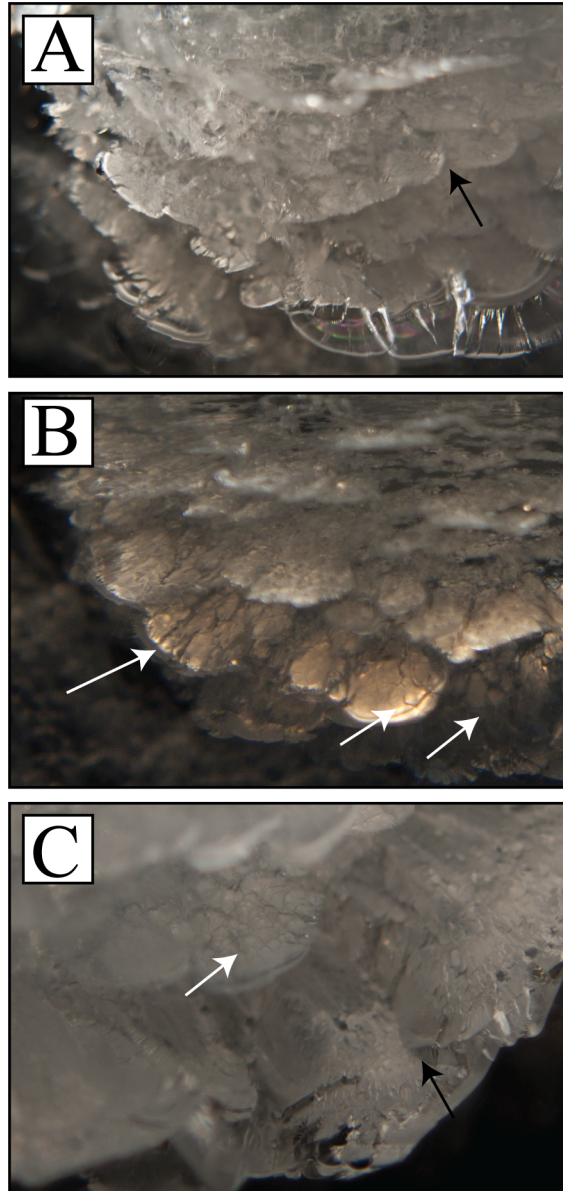


Figure 18

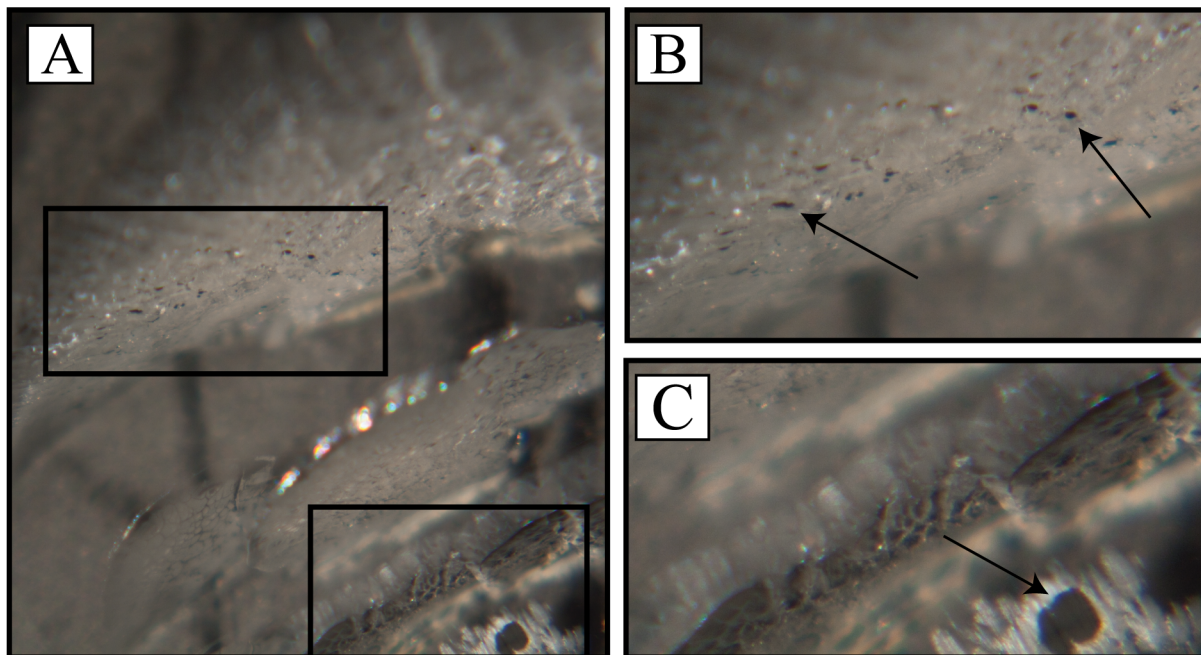


Figure 19

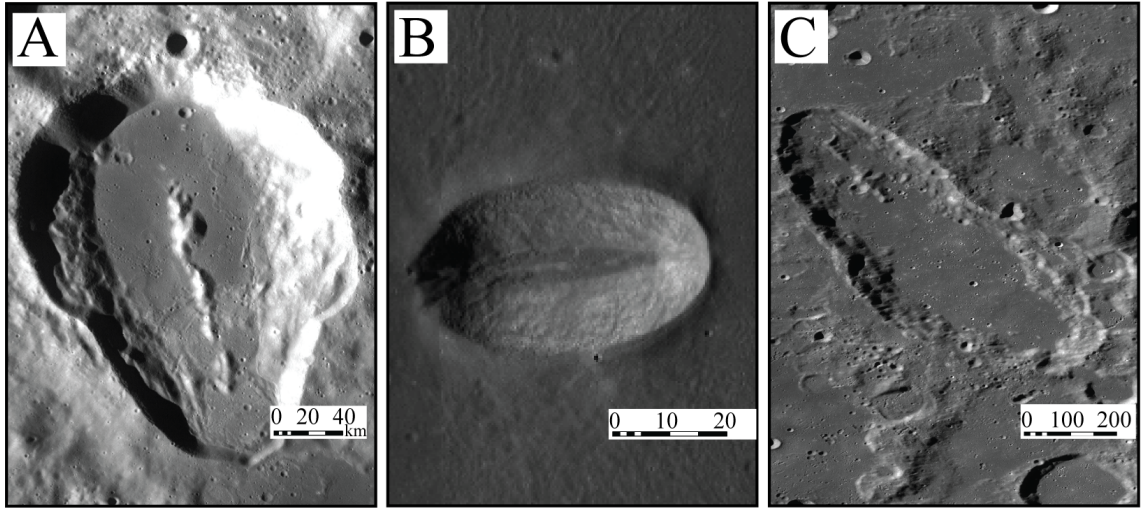


Figure 20

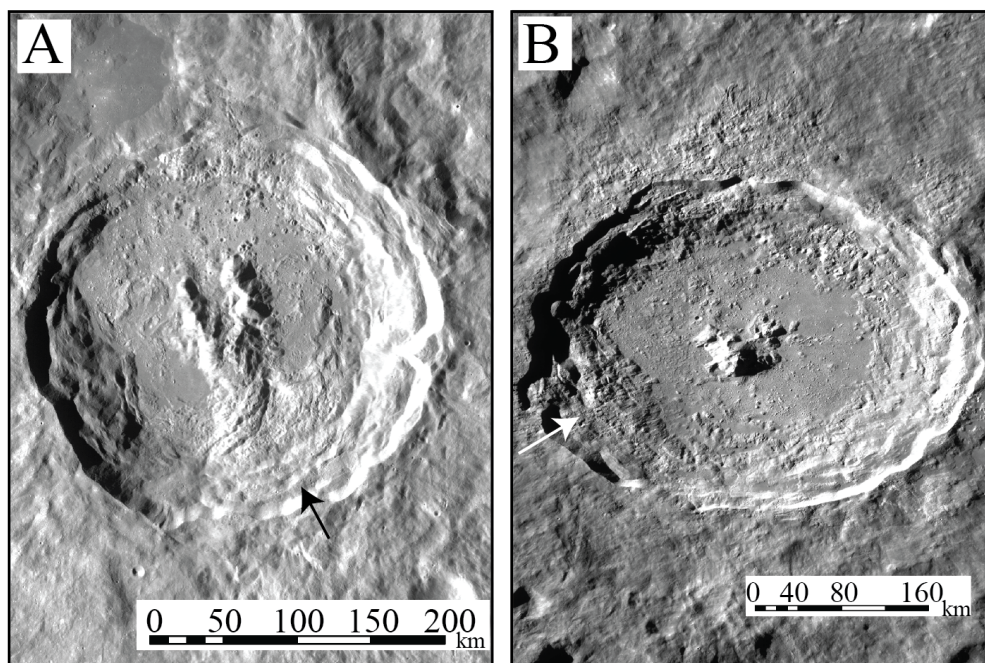


Figure 21

Chapter 3

Subsurface damage from oblique impacts into low-impedance layers

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Abstract - Layered planetary surfaces occur ubiquitously in the solar system, where sedimentary sequences or icy layers overlay crystalline bedrock. Previous experimental studies investigated how the presence of weak layer overlying a strong basement affects crater morphology, subsurface damage and soft-sediment compression. Numerical studies generally focus on the final morphology as a function of thicknesses and burial depths of weak layers. In field studies of impact craters, the shock state of minerals is a key metric. Here, we evaluate the effect of a surficial low-impedance layer on peak pressure magnitudes and consequent damage extent in the competent substrate. Laboratory experiments coupled with 3D CTH models of oblique (30° from horizontal) hypervelocity impacts at laboratory and planetary scales show that surface layers with a thickness on the order of the projectile diameter shield the underlying surface and absorb/scatter $\sim 70\%$ of the impact energy. Numerical simulations reveal that surficial layers reduce peak pressure magnitudes within the subsurface by $\sim 60\text{-}70\%$, while damage in the substrate is due to shear failure. Sedimentary layers are more efficient shields than icy layers, but both reduce the extent of subsurface damage and the resulting shock levels recorded by minerals. These results indicate that a thin surficial low impedance layer mitigates the expression of shocked minerals in the substrate even when a structural response is still observed.

INTRODUCTION

Layered terrains are ubiquitous in the solar system. Planetary surfaces such as Mars and the Earth are covered in sedimentary sequences, including unconformable icy layers. On Mars, thick unconformable layered deposits cover broad regions, some undergoing

exhumation [e.g., Schultz and Lutz, 1988; Greeley *et al.*, 1992; Kolb and Tanaka, 2001; Niles and Michalski, 2009] while thick, layered mixtures of ice and dust drape the two poles [e.g., Byrne, 2009 and references therein; Cutts, 1973; Herkenhoff and Plaut, 2000; Murray *et al.*, 1972; Phillips *et al.*, 2008; Plaut *et al.*, 2007]. On Earth, deposits (both lithified and unlithified) cover continental regions while thick ice sheets cover the polar regions. The impedance of sedimentary layers is generally lower than the underlying bedrock (where impedance is defined as the product of the uncompressed density and the sound speed). For low-angle impacts (e.g., $<30^\circ$), significant contrasts in impedance, such as surface deposits, could affect the diameter of the crater and the damage recorded in the substrate [Schultz, 2006; Schultz, 2007].

Early experimental studies at the NASA Ames Vertical Gun Range investigated effects of weak particulate layers overlying strong layers on crater diameter, substrate damage and soft-sediment compression. Oberbeck and Quaide [1967] used crater morphologies to infer past layering on planetary surfaces. Small-scale experiments revealed that changing the thickness of the surface layer relative to the crater diameter could reproduce different crater morphologies found on the lunar surface. This work allowed estimating the layer thickness from size-frequency distributions of various crater types.

Numerical studies examining the effects of layered targets on the cratering process generally focus on how the final crater morphology is altered by different types, and thicknesses, of low-impedance layers for specific crater structures [e.g., Artemieva *et al.*, 2004 (Bosumtwi); Collins and Wünnemann, 2005 (Chesapeake); Collins *et al.*, 2008 (Ries, Haughton, El-gygytgyn); Crawford *et al.*, 2004 (Chesapeake); Kenkmann *et al.*,

2005 (Upheaval Dome); Pierazzo and Melosh, 1999 (Chicxulub); Shuvalov *et al.*, 2005 (Lockne); Wünnemann *et al.*, 2005 (Ries)]. A study by Collins *et al.* [2008] reveals that major structural differences in mid-sized terrestrial craters, such as Haughton and Ries, can be explained by differences in the thickness, or absence, of pre-impact sedimentary cover. The authors find that both the transient and final crater diameters increase with sediment thickness for vertical impacts of equivalent energy.

Other studies assess morphology changes in a broader sense. In a study using CTH to examine icy-layered terrains on Mars, Senft and Stewart [2008] modified properties of a subsurface ice layer (thickness, ice fraction and depth) in order to investigate changes in crater morphology between glacial and interglacial periods. Their simulations of vertical impacts suggest that many of the odd or unusual crater morphologies that are seen on Mars might be explained by the presence of a near-surface ice layer. In the case of a surface-ice layer, crater formation proceeds similarly to an impact into basalt. For a very thick ice sheet, the ice separates from the basalt ejecta, thereby creating an inner crater in the basalt and an outer crater in the overlying ice analogous to the smaller nested craters on the moon. Their results also indicate the lower impedance surface ice layers may lead to slightly deeper craters overall (from the pre-impact surface, including the surface layer) compared to vertical impacts directly into basalt, whereas buried ice layers can lead to craters that are shallower than expected.

In a separate study, Senft and Stewart [2007] used CTH simulations to illustrate how a weak regolith layer over basalt also can affect final crater morphology. In this case, the layer was significantly thicker than the projectile diameter: a thickness of 10 m compared to projectile diameters of 0.5-1.75 m. This study replicated the morphologic variations

observed in small lunar craters (for vertical impacts), as interpreted from experimental results by Oberbeck and Quaide [1967] and Quaide and Oberbeck [1968].

While these studies concentrated mainly on specific crater structures or final morphologies, here we discuss the measurable quantities left in the rock record when the surface layer thickness is on the order of the projectile diameter. The goals of this study are two-fold: first, to compare model results to experiments at laboratory scale in order to determine what parameters are well matched. We focus on the effects of impact angle ($15\text{-}30^\circ$) and the material composing the surficial layer on subsurface deformation. Second, models at large-scale determine what features and processes match the small-scale experiments. This comparison then allows an explanation of large-scale models based on intuition from the laboratory. Specifically, we concentrate on the damage in, and peak pressures experienced by, the competent substrate, which may be the only evidence after erosion on Earth or Mars. Shock levels in minerals and the extent of subsurface damage provide clues for the surface materials, now removed.

METHODS

We use a combination of laboratory experiments and three-dimensional CTH models to study the effects of thin, surficial low-impedance layers. The CTH models are not meant to match the exact structures seen in laboratory experiments, but rather to inform about the processes behind them: numerical models allow peak pressures to be tracked for a variety of impact conditions at both small and large scales. The experiments, which provide the initial insight into the effects of low-impedance surface layers, also provide

an important reality check for the models and reveal details of failure structure and morphology.

Laboratory Experiments

The Ames Vertical Gun Range (AVGR), located at the NASA Ames Research Center in Mountain View, CA, uses a two-stage hydrogen light gas gun capable of firing projectiles with velocities ranging from 0.5 to ~ 7 km/s (depending on projectile size). The target chamber has a 2.5-m diameter and is able to accommodate a wide variety of target types and setups. The chamber can be maintained at a vacuum level below 0.3 torr or can be filled with a variety of gasses to simulate different environments. High-speed cameras (up to 1 million frames per second) are used to record impact events. One of the unique characteristics of the AVGR is the ability to change the impact angle from 0-90°, in 15° intervals, while keeping the target oriented correctly with respect to gravity (other angles can be achieved by tilting the target slightly). This is especially important when experiments involve particulate targets or fluids, and allows assessing oblique impacts into a variety of target types.

Transparent polymethylmethacrylate (PMMA) targets provide a unique opportunity to track the failure evolution and map the final damage structures within the target, something that is not easily done with rock or metal targets. At room temperatures and high strain-rates, PMMA is brittle and has mechanical properties similar to rocks at the surface of the earth; consequently, it is an ideal rock analog for laboratory studies [Li and Lambros, 2001; de Joussineau *et al.*, 2003; Rittel and Brill, 2008; Dorogoy *et al.*, 2010]. PMMA and other similar polymeric materials, in addition to their mechanical properties,

also exhibit birefringence, which makes them useful for studies of dynamic failure processes in rock [e.g., Li and Lambros, 2001; de Joussineau *et al.*, 2003; Misra *et al.*, 2009; Rosakis, 2002, Rosakis *et al.*, 1999; Rosakis *et al.*, 2004; Rosakis *et al.*, 2008].

For the present study, planar targets were 15 x 15-cm cast Acrylite blocks with thicknesses ranging from 5 cm to 6.35 cm. Targets with non-uniform geometry were constructed separately, including layered targets, and the acrylic blocks were placed on a Styrofoam block to minimize free-surface effects below. In order to determine the effects that low-impedance layers have on the cratering process (and damage growth in particular), several different layer geometries were considered. Layer thickness ranged from about one to two times the projectile diameter (i.e., $1a$ to $2a$). The experiments presented in this study were conducted at impact angles of 15° and 30° above horizontal with impact velocities ranging from 5.2-5.7 km/s, with 0.635-cm Pyrex spherical projectiles. Plasticine (Sculpture House premium Plastilina clay), pumice powder and ice layers with thicknesses ranging from 0.635 cm to 1.25 cm on top of the acrylic blocks mimic layered surfaces on planetary bodies. To create the layered targets, pumice powder was poured onto the top of the block, and Plasticine layers were rolled out into specific thicknesses and pressed onto the PMMA blocks. In order to create ice layers, a layer of water was frozen onto the block overnight. Table 1 summarizes the experimental conditions for the eight experiments detailed in the results section. The damage growth was imaged at frame rates from 250,000-500,000 frames per second.

CTH Models

CTH is a multi-dimensional, multi-material, two-step Eulerian hydrocode developed by Sandia National Laboratories [McGlaun *et al.*, 1990] where the Eulerian mesh is fixed in space, allowing the material to flow through it. The first step utilizes a Lagrangian mesh that deforms as the material moves, and the Lagrangian forms of the governing equations are solved. In the second step, the deformed mesh is then remapped into the original Eulerian mesh. The code is designed to model strong shock, large deformation events so that the user can choose from a range of equations of state (EOS) and material models.

Tracking failure during oblique hypervelocity impacts requires an accurate failure model to understand failure processes and damage accumulation. Unfortunately, it is somewhat complicated to track both shear failure and extensional failure simultaneously. Therefore, failure due to shear deformation is tracked separately from failure due to tension [e.g., Stickle and Schultz, 2011; Stickle *et al.*, 2009]. The models used for this study assume linear, isotropic elasticity and von Mises plasticity with an associated flow rule where the plastic strain is everywhere normal to the yield surface.

Three-dimensional models are used for 1:1 comparisons between laboratory and numerical experiments using identical impact conditions to the experiments. The calculations use a Mie-Grüneisen EOS for the Pyrex impactor [Marsh, 1980], PMMA block and Styrofoam base (both are available within the CTH package). Plasticine was modeled using a Mie-Grüneisen EOS after Thomsen *et al.* [1979], while the ANEOS package [Thompson, 1990; Thompson and Lauson, 1984] was used to model ice layers. A summary of equation of state and material model parameters used in these models is

shown in Table 2. Parameters that were not used in the model, or undefined (such that default values were used), are left blank.

For laboratory-scale models, Pyrex projectiles were modeled using a pressure yield surface that incorporates thermal softening and density degradation. The model assumes that Pyrex fails like a geologic material, which is sufficient for this study for modeling the projectile breakup following impact. Because extensional and shear failure must be tracked separately, a slightly more complicated strength model was necessary to model failure in the PMMA substrate; consequently, two separate failure criteria were used. Extensional failure occurs when the stresses exceed the tensile strength of the material, i.e., spallation. The Johnson-Cook fracture (JCF) model is used to illustrate regions undergoing shear deformation. JCF is a scalar damage model that predicts failure of materials due to equivalent plastic strain as a function of pressure, temperature, strain rate and loading path. Plastic strain and damage begin accumulating in the material when it experiences stresses greater than the yield strength. Shear failure ($D=1$, and a complete loss of strength) then occurs when the material reaches a specified value of plastic strain [Johnson and Cook, 1985]. A parameter study was undertaken to determine material properties that provide the best match to laboratory impact experiments [Stickle and Schultz, 2011], and thus complete failure is assumed to occur at 10% plastic strain. This model is used alongside the spall model for predicting overall failure in the substrate. The PMMA here is assumed to have a yield strength of 120 MPa (based on results in Stickle and Schultz [2011] and dynamic experiments in PMMA [e.g., Dorogoy *et al.*, 2010]). The two different failure criteria are run independently, providing a more complete picture of the overall failure within the PMMA. Plasticine and ice layers were both

modeled using a pressure-dependent strength model for geologic materials [Austin *et al.*, 1980; Christensen *et al.*, 1968; Gold, 1977].

Comparisons between the small-scale experiments and hydrocode results provide insights for models at much larger scales. In this case, basalt replaced PMMA as the competent substrate. Three separate cases were examined: 1) a 1-km dunite sphere impacting into a basalt target; 2) a 1-km dunite sphere impacting into a 1-km thick ice sheet over basalt; and 3) a 1-km dunite sphere impacting into a 1-km thick sediment layer over basalt. Basalt was modeled using ANEOS and a pressure-dependent yield surface for a geologic material, with strength parameters from Cohn and Ahrens [1981]. To determine whether a damage model was necessary to accurately track strain and peak pressures for these large-scale models, a comparison was made between a model with a simple damage model comparable to the laboratory-experiments and one without a damage model. The extent of damage, strain magnitudes, and peak pressures were virtually unchanged. Therefore, for simplicity, the damage model was not included in the other large-scale simulations. The material models for the low-impedance layers (ice, and Plasticine as a proxy for sediments) were identical to the small-scale models. Plasticine was chosen as a proxy for sedimentary rocks for two reasons: 1) it provides a more direct comparison to the small-scale laboratory experiments, and 2) it has an impedance similar to dry sedimentary rocks. To ensure the validity of this comparison, two models were compared: an impact into a Plasticine layer over bedrock, and an identical impact into a sandstone layer over bedrock. The peak pressure magnitudes and peak-pressure decay in the substrate were nearly identical (Figure 1). Here, the substrate

was modeled as granite. A pressure-dependent yield surface and a density-scaled α -quartz sesame table were used for both granite and sandstone.

All of the calculations were performed in a 3D rectangular coordinate system. This setup allows oblique impacts to be examined in detail. Adaptive Mesh Refinement (AMR) [Crawford, 1999; McGlaun *et al.*, 1990] resolves small-scale details within the model at a high-resolution and reduces computation time without requiring a high-resolution mesh over the entire grid. The mesh is refined in specific regions according to user-defined indicators; for example, the shock front may be resolved to a high degree while leaving the edges of the target at a low resolution, thereby saving computation time. For the laboratory-scale simulations, the maximum resolution was .08 cm (~8 cells across the projectile), while the large-scale simulations had a maximum resolution of 31 m (~32 cells across the projectile). Mass-less Eulerian tracer points were placed throughout the model to track the history of the target material through time. Resolution studies for similar models [Stickle and Schultz, 2011] reveal that increasing resolution increases the final damage extent slightly and that high-resolution models appear slightly weaker. The “low-resolution” models in Stickle and Schultz [2011] have similar resolution to the small-scale models here and are sufficiently resolved to constrain the limits of damage in experiments. Mesh resolution may also affect tracking of the shock wave and absolute pressure magnitudes; this is discussed in more detail in section 4.

RESULTS

Laboratory Experiments

A suite of laboratory experiments at the NASA Ames Vertical Gun Range revealed the effects of layer thickness and layer type on damage resulting from hypervelocity

impacts. As described below, the presence of a low-impedance surface layer significantly affects the damage seen in the underlying, competent substrate. Similar effects are observed in the hydrocode simulations, but with some significant differences.

Because PMMA turns opaque when it is damaged, it is relatively easy to visualize subsurface damage. Figure 2a-f shows top views of the damage resulting from 30° impacts into PMMA blocks with varied materials and thicknesses as low-impedance surface layers. The images show the competent substrate (here, the PMMA block) after the low-impedance layer was removed. The dashed black lines outline the approximate crater shape and size in the competent substrate, the dashed line outlines the boundaries of the “spall region” and the dotted line outlines the extent of the damage on the surface.

Without a surface layer, the damage is relatively circular and the crater is oblong along the impact trajectory (Figure 2a). A one projectile-diameter-thick (i.e., $1a$, where a is the projectile diameter) Plasticine layer reduces the crater size, symmetry, and the overall extent and depth of the main damage region (Figures 2c and 5). If the layer thickness is increased to two projectile diameters (thickness= $2a$: here, 1.27 cm; Figure 2e), no damage occurs in the competent substrate. Similar responses occur for pumice and ice layers. For a thickness equal to one projectile diameter, both the subsurface damage and crater size in the competent substrate are drastically reduced (Figures 2b and 2d); for the case of a pumice layer (Figure 2b) there is minimal damage in the substrate and no crater at all. When a 1.27-cm ice layer (thickness= $2a$; Figure 2f) is present, most of the damage in the subsurface is concentrated downrange. The area directly beneath the impact point (the “main damage zone” shown in Figure 5) has no damage and there is not a crater present, similar to the case of the $2a$ -thick Plasticine layer.

These results indicate that more energy is coupled into the Plasticine layer than a comparable ice layer for an oblique impact (Figure 3). The distance was measured from the projected impact point on the interface between the subsurface and the layer (a schematic is shown in Figure 3b) in order to compare damage extent in the competent substrate between layered and unlayered targets. In all cases, the plots reveal that impacts into layered targets result in smaller final damage zones than impact directly into PMMA (e.g., Figure 2b). Further, Plasticine and pumice layers more effectively shield the subsurface than ice (Figure 3a). As expected, thicker surface layers result in less damage (Figure 3c and 3d).

Experiments at an angle of 15° above the horizontal show the damage resulting from an impact directly into a planar PMMA target (Figure 4 top) compared with an impact into a 1a-thick Plasticine layer over a planar PMMA target (Figure 4 bottom). As expected, the overall damage extent for a 15° impact is less than the damage from a 30° impact because more of the energy and momentum is decoupled with the impactor [Schultz and Gault, 1990a; Schultz and Gault, 1990b; Schultz and Gault, 1991; Schultz and Crawford, 2008]. A 1a-thick Plasticine layer atop the PMMA target, however, results in zero subsurface damage beneath the impact point, and no crater is formed. Like the 30° ice impact, there is minimal damage in the form of shallow, concentric cracks downrange.

A low-impedance layer causes changes in the evolution of the damage zone relative to impacts into PMMA only. Figure 5 and Figure 6 reveal the evolution of damage growth for the case of an impact into PMMA, with and without a surface layer (one-projectile-diameter) of Plasticine, respectively. Directly following impact into PMMA, a

small region of bubbles forms near the surface behind the shock wave (Figure 5, 4 μsec). A hazy region of damage containing many semi-parallel, subarcuate failure planes quickly follows at 8-12 μsec [see also Stickle and Schultz, 2010]. This damage zone initially grows into the target from uprange to downrange. Approximately 12 μsec after impact, a “tongue” of damage extends into the target roughly following the initial trajectory, but wraps around to either side, reducing in depth uprange. The shock wave reflects from the bottom of the target 20-30 μsec after impact (dependent on target thickness), resulting in a region of tensile failure paralleling the target surface on the bottom. The damage finished growing between 40-50 μsec after impact, leaving behind three main damage regions: the main damage zone beneath the impact point and crater; the downrange, diving “tongue”; and the tensile failure at the base of the target.

The low-impedance layer alters damage evolution considerably (Figure 6). Because the shock wave must first travel through the surface layer, damage in the substrate begins later. It is also significantly reduced and shallow. The damage due to the passage of the shock wave is confined to a small region near the surface, emerging approximately 30 μsec after impact. Damage begins where the projected line of trajectory intersects the surface of the PMMA and grows downrange. The reflection of the shock wave again results in significant damage at the base of the block and, in this case, near the surface. Most of the subsurface damage results from the reflected shock wave (revealed in the top view; Figure 2c). Although not strong enough to induce damage initially, the rarefaction off the bottom surface results in significant damage due to the prestressed state behind the shock. This is not the case for all layered targets. For example, a one-projectile-diameter pumice layer on the PMMA target (Fig. 2b and Fig. 3b) absorbed and

scattered the initial shock. Even though the PMMA below is weakened, no rarefaction damage occurs.

CTH Simulations and Comparisons with Experiments

Numerical models paralleling the experimental series reveal the underlying physical processes and conditions. Understanding these processes provides a better understanding of large-scale computational experiments and the planetary impact record. It is important to note that we are not attempting to predict (nor perfectly match) the morphology and complicated structures seen in our experiments. Rather, the models are used to provide insight into the physical processes responsible for those structures, specifically the pressure and strain experienced by the target material.

As a first step, 1:1 comparison models were calculated with initial conditions identical to the experiments while tracking properties such as failure, damage, stress and strain history. As before, the Johnson-Cook Fracture model [Johnson and Cook, 1985] was used to assess regions of shear failure in the target with the failure criterion set in terms of equivalent plastic strain to failure (again, assumed to be 10% strain). The evolution of strain provides a proxy for the failure occurring following an impact. This is separate from, but similar to, the scalar damage parameter, D , which indicates failed material at $D=1$. In conjunction, models are useful to understand the pressure and temperature history through time.

The strain evolution from the model can be combined with a corresponding time sequence from laboratory experiments (e.g., Figure 7). For a one-projectile-diameter thick ice layer on top of the PMMA substrate, the CTH simulations reveal large amounts

of plastic strain in the central damage zone. This correlation indicates that the subsurface damage is due to shear failure (Figure 7). The models show a reduced damage zone compared to an equivalent impact directly into PMMA, in agreement with experiments.

Figure 7 and Figure 8 show time sequences from AVGR experiments and equivalent CTH model results for a 1a- and 2a-thick surface ice layer, respectively. The model variables shown are plastic strain (middle) and pressure (right). Most damage forms behind the shock wave and is basically finished forming well before the rarefaction off the bottom surface returns. Damage begins while the material is still under compression, before the unloading behind the shock wave (based on the companion numerical model). Just as in the experiments, the damage grows asymmetrically. The CTH comparison in Figure 8 predicts a fairly substantial central damage zone. In contrast, inspection of the resulting damage in the AVGR experiment shows a hollow, arcuate damage region downrange. While the general extent of damage in the model matches that in the experiment, the location and structure do not: the central, sub-impact damage zone is absent in the experiment.

Second, a series of laboratory-scale models isolated how a specific layer type or thickness affected the peak pressures experienced by, and energy deposited into, the substrate. Four separate cases were examined: a) no layer, impact directly into PMMA; b) a one-projectile-diameter (1a) thick Plasticine layer on top of the PMMA; c) a 1a-thick ice layer on top of the PMMA; and d) a 2a-thick ice layer on top of the PMMA. All four cases used a 0.635-cm Pyrex projectile impacting at 5 km/s at an angle of 30° above the horizontal. The yield strength for PMMA was taken to be 120 MPa, and failure in the PMMA occurred at 10% plastic strain. As in the experiments, the model includes a

Styrofoam block below the PMMA block. Figure 9 shows a comparison of plastic strain accumulated in the substrate 50 μ sec after impact, following the completion of damage formation. As expected, the surface layers act to mitigate damage, and in agreement with the experiments, the Plasticine layer shields the subsurface better than an equivalent ice layer. These simulations demonstrate that the primary zone of damage in the experiments is due to large amounts of plastic strain, not purely tensile failure, although the specific expressions of failure are not matched.

Peak pressure with depth can be easily tracked in numerical models. Figure 10 and Table 3 document the peak-pressure decay with depth for each of the four lab-scale model geometries illustrated in Figure 9. Mass-less Eulerian tracers at specific locations within the PMMA substrate tracked the peak pressures (Figure 10). Unsurprisingly, the case with no surface layer exhibits the highest peak pressures. In general, the peak pressure magnitude is also greater downrange than directly beneath the impact point as a result of the downrange-directed shock wave. Further, a thicker layer shields the subsurface from damage (reduced peak pressures) better than a thinner layer does for a given material (ice in this case). A 10% lower impedance in the surface layer compared to PMMA (i.e., an ice layer) results in the peak pressure dropping by $\sim 43\%$, whereas a $\sim 30\%$ lower impedance (Plasticine) results in the peak pressure dropping by 27% at a depth equivalent to 1.5 projectile diameters. By three projectile diameters, the presence of a 1a-thick ice layer causes a 35% decrease in peak pressure and a 1a-thick Plasticine layer results in a 43% decrease.

These results indicate that a thin Plasticine layer (one projectile diameter) at the surface is enough to significantly reduce the peak pressures in the substrate (see, for

example, Figure 2 or 3) with subsurface damage significantly reduced below the impact but accentuated farther downrange. A one-diameter-thick layer of Plasticine is a more effective shield than a two-diameter-thick layer of ice.

Large-Scale Models

Large-scale models provide insights for interpreting the cratering record. Three different cases were examined: 1) 1-km diameter dunite sphere impacting into a basaltic substrate; 2) 1-km dunite sphere impacting into a 1-km thick sediment layer on top of a basaltic substrate; and 3) 1-km dunite sphere impacting into a 1-km thick ice layer on top of a basaltic substrate. All three cases used a speed of 15 km/s and an impact angle of 30° (above the horizontal). Figure 11 shows pressure contours 1 second after impact for each case. The top images show material isosurfaces overlain with pressure values, whereas the middle and bottom rows show pressure contours perpendicular to the trajectory and parallel to the trajectory, respectively. The low-impedance sediment (represented here by a Plasticine layer) and ice layers act to shield the competent basalt substrate. Peak pressures and the extent to which material is shocked are reduced.

In the model simulations, mass-less Eulerian particles track the evolution of pressure with distance from the impact point (shown schematically in Figure 12) with the resulting pressure decay shown in Figure 13. Figures 13a and Figure 13b shows maximum pressure with depth, directly below the point of first contact. The vertical, dashed black line indicates the location of layer-basalt interface for the two different layered cases. The impact directly into the bedrock has the highest peak pressure, but decays to a value approximately equal to that of ice. The presence of a sediment layer significantly reduces

the pressure magnitude far from the impact point (Figure 13b). Downrange from the impact point, this difference increases drastically (Figure 13d). Pressure evolution through time at a point directly beneath the impact point and 1-km deep in the substrate are shown in Figure 13c. Not only does it take much longer for the material to experience the peak pressure, but the pressure is also very much reduced. This again shows that sedimentary layers more efficiently shield the substrate than do ice layers. Specifically, Table 4 shows peak pressure magnitudes from the CTH simulations shown in Figure 11. An 85% lower impedance (ice above bedrock) results in the peak pressure dropping from ~12 GPa to ~5.5 GPa (reduced by 55%), whereas a 90% lower impedance (sediment above bedrock) results in the peak pressure dropping from 12 GPa to ~3 GPa (reduced by 70%) near the surface of the bedrock. This difference increases markedly with distance from the impact point.

DISCUSSION

In summary, both experimental and numerical results reveal that even a relatively thin (1-2a) low-impedance surface layer significantly reduces subsurface damage in the target for an oblique impact. Both the overall damage zone and crater size are reduced (even non-existent in some cases). Thicker layers more effectively shield the underlying competent substrate, but even a layer on the order of 1-projectile-diameter has measureable effects (for a 30° impact). Laboratory experiments into layers of Plasticine, pumice powder and ice overlying planar PMMA targets show subsurface damage structures distinct from those due to an impact directly into PMMA. Companion CTH models demonstrate that these differences (morphology and extent) are due to reduced

peak shock pressures in the substrate as significant amounts of energy are absorbed/scattered in, or directed along, the surface layer.

The three large-scale simulations illustrate what might remain following post-impact modification and erosion of a layered surface. Masking the surface layer provides visualization for the eroded surface. Figure 14 shows the plastic strain experienced by the substrate 1 sec after impact for the three large-scale CTH models. Here, the substrate surface is shown at an equal height for all three geometries. These results are early in the cratering process, but note that the depth of the crater here is similar to the maximum depth of modification [Elbeshausen *et al.*, 2009, Fig. 1]. Figure 14 allows comparison between an impact into basalt (Figure 14a), into a 1-km-thick sedimentary layer (Figure 14b), and into a 1-km-thick ice layer (Figure 14c). The surface layer and approximate crater have been masked to show the level of strain in the substrate following post-impact modification and erosion. These results illustrate how an oblique impact into a low-impedance surface layer can mitigate shock damage in crystalline basement rocks, thereby complicating assessment of the initial crater size, if not confirmation of an impact structure. For example, quartz begins to display shock features at pressures above the HEL (between 5-7 GPa), and remains in the low-pressure regime until ~35 GPa [Stöffler and Langenhorst, 1994]. The lowest pressure regime occurs before the change from α -quartz to high-pressure phases, within a range from 5-14 GPa. Weakly (or ambiguous) shocked minerals within a structural disturbance can weaken the identification of an impact structure.

Qualitatively, Figure 14 can also be compared to the results in Senft and Stewart [2008], which indicated that vertical impacts into an ice-over-basalt target resulted in

slightly deeper craters when compared to vertical impacts directly into basalt. The models here, however, indicate the opposite for oblique impacts. Craters directly into basalt are slightly deeper than equivalent impacts into a low-impedance layer (either ice or sediment) over basalt when measured from the pre-impact surface. This is likely a result of the surface layer absorbing and scattering a greater percentage of the initial impact energy for an oblique impact (Figure 15).

The Rock Elm structure in Wisconsin, USA illustrates the possible role of low-impedance surface sediments. French *et al.* [2004] identified quartz exhibiting features characteristic of shock levels between 5-10 GPa in the central region, well within the low-pressure regime. French *et al.* [2004] used crater-scaling to conclude that a crater the size of Rock Elm could have formed from a stony meteorite approximately 200 m in diameter impacting the surface at 30 km/s at an angle of 45° (4×10^{18} J). Our large-scale CTH simulations, however, predicts a larger projectile with $\sim 4 \times 10^{22}$ J (Table 4) in order to produce the same transient crater depth.

Simulations with a surficial low-impedance layer mitigate peak pressure in the substrate enough to remain within the low-pressure regime, and, more specifically, within the 5-10 GPa range. The geology of the Rock Elm structure includes several hundreds of meters of sediments over the crystalline Precambrian basement [French *et al.*, 2004]. The estimates for projectile size and pre-impact stratigraphy by French *et al.* represent a low-impedance layer with a thickness of 2-3a overlying more competent bedrock, which is a geometry comparable to the experiments and small-scale models considered here. The large-scale models examined here, however, evaluate a 1-km projectile impacting obliquely into a 1a-thick sedimentary layer, which is significantly larger than the

estimates in French *et al.* [2004], but results in similar pressure magnitudes. This suggests that the impactor in this case may have been much larger than 200-m in diameter if it impacted at an oblique angle because of the shielding provided by the surface layer. These results suggest one possible explanation for the absence of highly shocked material within the impact structure: the sediments scattered and absorbed a significant amount of the impact energy from an oblique impact. Thus, the underlying competent rocks were shocked to weaker pressure. In the case of Rock Elm, up to 300 m of this sediment has since been eroded, reducing the remnant crater size [French *et al.*, 2004].

The water depth at time of the Rock Elm impact event is unknown; so, it has been neglected in the models. Nevertheless, the effect of water-saturated sediments is instructive. Wet sediments typically have densities ranging from 1.9-2.4 kg/m³. This is higher than the density of dry sediments (1.69 kg/m³) used in our models, and would act to increase the acoustic impedance of the surface layer by up to ~70%. This could possibly, in turn, decrease the shielding effects. However, the difference between the wet sediment impedance (~3.4-4) and the impedance of the underlying bedrock (~17) is still significant, so it is unlikely to alter the results seen here.

Numerical models also can be used to better understand energy deposition following an impact. Specifically, a simulated 30° impact at ~5.5 km/s matches the laboratory experiments using a layered target (Figure 15). The model reveals that approximately 70-75% of the initial energy of the system is deposited into the 2a-thick Plasticine layer (here, 1.27 cm thick). Over time, this averages out to ~60-70% of the total internal energy localized in the Plasticine layer. Very little of the initial kinetic or final internal energy is

deposited into the competent substrate. The reduction in subsurface damage is one manifestation of the energy being absorbed/scattered in the surface layer.

In general, inadequate spatial resolution can affect the results of numerical experiments. Specifically, a low-resolution, 3D simulation will reduce the intensity of the recorded peak shock pressure because the shock parameters are averaged over the cell volume. Thus, higher resolution results in smaller cell volume and sharper shock boundaries. For 3D CTH simulations, Pierazzo [2006] showed that a resolution of 5 cells per projectile radius (cpr) results in a 20% lower measured peak pressure than the same simulation with 20 cpr. The peak pressures measured in these simulations, therefore, must be considered a lower estimate. However, because equivalent resolution is used for comparison models (i.e., laboratory-scale models with differing layers), the relative values are still comparable. Further, the key observations of energy coupling and damage reduction are essentially unchanged by absolute magnitude of peak pressure.

Laboratory experiments reveal that the pumice is an effective shield when compared with ice or other, non-porous sediments (Figures 2 and 3). This increased shielding may be an effect of pore-space collapse as the shock wave travels through the pumice layer, or it may reflect a transformation of impact energy into kinetic energy of the ejecta (for pumice) rather than internal energy of deformation (for ice or Plasticine). However, the CTH simulations considered in this study do not include porosity, and therefore may overestimate peak pressures (which may also offset resolution effects). In a porous rock, peak pressures may decay more quickly than in a crystalline rock, and so the values presented here may provide a worst-case scenario. The interaction of porosity and resolution effects has not yet been quantified.

Some discrepancies do still remain between the observed damage in the target in experiments vs. damage predicted by the numerical models. First, the simulations do not fully capture the complete damage zone because neither the downrange “tongue” nor the full spall region are not seen in any simulation, even though the overall central region damage is of similar extent. Second, a two-projectile-diameter thick Plasticine layer in the laboratory experiments did not produced any subsurface damage (Figure 2e). A two-projectile-diameter thick ice layer, however, did result in very minimal damage (Figure 2f), which may be due to edge effects. The CTH simulations, however, predicted damage in both cases; hence, the model over-predicts the extent of the damage zone. This implies that damage may be even more reduced in both small- and large-scale simulations than what is currently seen in the figures. This might be due to several factors. First, it is likely that projectile failure is not being accurately modeled in these simulations. Previous experimental work [Schultz and Gault, 1990a; Schultz and Gault, 1990b] revealed that, for oblique impacts, a significant portion of the projectile energy (up to 50%, dependent on velocity) is decoupled from the initial impact by decapitation of the projectile. This is especially pronounced at low angles (5-15°). If this process is not fully captured in the simulation, the initial amount of energy being coupled to the target may be too high, resulting in an excess of damage. Second, these impacts cannot be treated as a point source; rather, the impactor transfers energy through continued penetration and successive impacts by pieces of the disrupted projectile [e.g., Schultz and Anderson, 1996]. In laboratory experiments using layered targets, a low-impedance layer shields the substrate from the complete process of energy and momentum transfer; this has not been observed in the lab-scale simulations.

CONCLUSION

Laboratory experiments coupled with 3D CTH models show that, for a layered target, surface layers with thicknesses approaching the projectile diameter act as effective “flack jackets” by shielding the underlying target material and absorbing or scattering significant portions (~70%) of the impact energy for a 30° impact. Numerical simulations reveal that this reduced (and often shallow) damage is due to shear failure, rather than purely tensile processes. Moreover, here we find that one-projectile-diameter-thick sedimentary or ice layers at the surface reduces peak pressures (and damage) within the substrate by ~60-70%, with sedimentary layers more effective in shielding than an ice layer. Both approaches indicate that a sufficiently thick, low-impedance layer may mitigate expressions of shocked minerals in the substrate within large-scale craters even though a structural response occurs. One example of this is the Rock Elm impact structure, which will be examined in much more detail in a future study.

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TABLES

Table 1. Experimental conditions from the AVGR experiments

Experiment Number	Target thickness [cm]	Layer	Impact Angle [deg]	Impact Velocity [km/s]	Projectile
081111	6.35	No layer	30	5.5	0.635-cm Pyrex
090618	5	No layer	30	5.2	0.635-cm Pyrex
090621	5	0.635-cm Plasticine	30	5.68	0.635-cm Pyrex
110107	5	1.25-cm Plasticine	30	5.45	0.635-cm Pyrex
110108	5	1.25-cm ice	30	5.39	0.635-cm Pyrex
110110	5	0.635-cm ice	30	5.71	0.635-cm Pyrex
110111	5	0.635-cm pumice powder	30	5.69	0.635-cm Pyrex
100621	5	No layer	15	5.2	0.635-cm Pyrex
110114	5	0.635-cm Plasticine	15	5.7	0.635-cm Pyrex

Table 2. EOS and material strength parameters used in CTH models.

Parameter	Pyrex ¹	PMMA ²	Plasticine ³	Ice ⁴	Foam	Basalt	Dunite	Granite	Sandstone ⁵
Density (g/cc)	2.23	1.186	1.69	0.919	0.035	2.86	3.32	2.68	2.1
Sound speed (km/s)	2	2.3	1.4	3.18	2.74	5.17	6.65	3.78	3.78
Linear coefficient of the Us-up Hugoniot curve: S1	1.5	1.75	2.978	--	1.319	--	--	--	--
Quadratic coefficient of the Us-up Hugoniot curve: S2	0	-0.13	-0.694	--	0	--	--	--	--
Gruneisen Parameter: Γ	1	0.91	1	--	1.18	--	--	--	--
Cv (erg/g/eV)	1x10 ¹¹	3.5x10 ¹¹	--	--	1.34x10 ¹¹	--	--	--	--
Yield Strength (MPa)	1000	120	0.05	15	0.5	250	250	250	50
Yield Strength at P=0 (MPa)	2	--	--	--	0	2	2	2	2
Poisson's ratio	0.26	0.37	0.44	0.3	0.25	0.26	0.26	0.26	0.26
Strain to Failure	--	10%	--	--	--	--	--	--	--
Mohr-Coulomb parameter (internal friction angle) at P=0: dy/dp	0.5	--	--	--	--	0	0	0	0
Melting Temperature, Tm (eV)	0.25	0.25	--	0	--	0.16	0.16	0.16	0.16

¹Marsh (1980); ²Stickle and Schultz [2011] and library coefficients; ³Christensen et al. [1968] and Austin et al. [1980]; ⁴Gold 1977; ⁵Ai and Ahrens [2004]

Table 3. Peak pressure magnitudes within the PMMA substrate for four different model geometries^a

Location	Depth [cm]	No layer [MPa]	1a ice [MPa]	2a ice [MPa]	1a Plasticine [MPa]
90 deg	1	440	253	226	319
	2	239	156	152	137
	3	171	117	116	77
	4	133	95	103	64
1 cm DR	1	1413	584	454	583
	2	489	285	232	200
	3	234	149	144	90
	4	158	119	121	76
2 cm DR	1	1118	867	503	436
	2	504	381	282	136
	3	264	175	168	138
	4	151	134	118	83

^aDepths are taken from the PMMA surface directly below the impact point, 1 cm downrange, and 2 cm downrange.

Table 4. Peak pressure with depth for large-scale layered CTH models

Layer	Impedance	Depth beneath rock surface [km]	Distance from impact point [km]	Peak P [GPa]
None ($\rho=2.82 \text{ kg/m}^3$)	~20	1	1	11.95
		2	2	6.92
		3	3	4.3
Dry Sediment ($\rho=1.69 \text{ kg/m}^3$)	2.366	1	2	3.39
		2	3	2.69
		3	4	2.23
Ice ($\rho=0.99 \text{ kg/m}^3$)	2.89	1	2	5.57
		2	3	4.26
		3	4	3.59

FIGURE CAPTIONS

Figure 1. Peak pressure with depth for four different layered models. Geometry is similar to assumed original stratigraphy for the Rock Elm impact structure [French *et al.*, 2004]. The models show results from an impact of a 200-m dunite projectile into a 200-m, 400-m, and 600-m thick Plasticine layer over a granitic bedrock (as a proxy for sedimentary rocks), compared with the results for the same impact into a 600-m thick sandstone layer over granitic bedrock. Impact velocity: 30 km/s, impact angle: 30° [after French *et al.* 2004]. Pressure magnitudes were taken directly down from the impact point. Note that sandstone and Plasticine result in virtually equivalent results.

Figure 2. Top view of 6 AVGR experiments showing the extent of subsurface damage. The solid black lines show the approximate outline and size of the crater, the dashed lines show the spall zone, and the dotted lines outline the extent of the damage on the layer interface (the top surface of the PMMA block). The arrows show the impact trajectory. Note that (a) has two crater outlines, showing a central, elongate, deeper region within the main crater structure. There is no spall zone or crater form in (b), or (e), and only a small region in (f). The orange lines in (f) show where the subsurface damage intersects the surface in discrete cracks.

Figure 3. Damage evolution through time. a) Comparison of experiments with 1 projectile diameter thick layers. b) Side view of final damage pattern following two different experiment setups. The dashed white line indicates the top of the block, while the dotted rectangle shows the pre-impact location of the pumice layer. (top) Impact directly into PMMA with no surface layer. Impact angle: 30° above horizontal (from right to left), impact velocity: 5.5 km/s. Measurements were taken from the impact point. (bottom) Impact into 0.635-cm (1a) pumice layer on top of PMMA target. The dashed yellow lines show the measurement geometry for a, c, d. The curves were measured along the 30° line in the substrate. Impact angle: 30° (from right to left), impact velocity: 5.7 km/s. The projectile size is shown for reference at the point of impact. Note that the final damage extent is significantly reduced when a layer is present. These two cases correspond to the “no layer” and “1a pumice” curves in a. c) Comparison of damage with two different thicknesses of Plasticine layers. Damage is significantly reduced when a 1a thick layer is present and there is zero damage when the layer thickness is equal to 2a. d) Comparison of ice layer thickness. Thicker layers of ice result in reduced damage, crater size and delayed damage formation.

Figure 4. (top) Damage following a 15-degree impact at 5.2 km/s into planar PMMA target without a surface layer. The solid line gives the approximate “crater” shape on the surface, the dashed line shows the beginning of the spalled region and the dotted line shows the approximate outline of the extent of the surface damage. The star indicates the approximate impact point, while the arrow shows impact direction. (bottom) Damage following a 15-degree impact at 5.7 km/s into a planar PMMA target with a 1 projectile-diameter thick layer of Plasticine on top. Note the lack of damage underneath the impact point when a low-impedance layer is present. The arrow indicates impact trajectory, and the star shows the approximate impact point on the surface layer.

Figure 5. Evolution of the subsurface damage through time for an impact directly into a planar PMMA target. Impact by a 0.635-cm Pyrex projectile at 5.5 km/s. Impact angle: 30° above horizontal. The white lines show the top and bottom of the target block, 6.35-cm apart. The size of the projectile is shown for scale. The three main damage regions described in the text are shown: the main damage zone, the downrange “tongue” and the tensile failure at the base of the block.

Figure 6. Evolution of the subsurface damage through time for an impact into a 0.635-cm (1a) Plasticine layer over a planar PMMA target. Impact by a 0.635-cm Pyrex projectile at 5.68 km/s. Impact angle: 30° above horizontal. The white lines show the top and bottom of the planar target (5 cm apart), the red arrow indicates impact trajectory, and the projectile size is shown for scale. Shock wave reflection damage begins at the bottom of the block, and grows upward to surround the shallow impact damage.

Figure 7. 1:1 comparison of an AVGR experiment to an equivalent CTH calculation. Size of projectile and trajectory are marked for reference. (left) Time sequence showing evolution of damage from a 0.635-cm Pyrex projectile impacting into a 0.635-cm (1a) ice layer over PMMA target. Impact velocity: 5.7 km/s, impact angle: 30° from the horizontal. (middle) Corresponding CTH calculation showing plastic strain. Failure occurs at 10% plastic strain, which is marked by a black line on the colorbar and is outlined by a black contour in the images. (right) Corresponding pressure contours. Positive values and warm colors indicate compression, while negative values and cold colors indicate tension.

Figure 8. 1:1 Comparison between an AVGR experiment and an equivalent CTH calculation. Projectile size and trajectory are marked for reference. (left) Time sequence showing evolution of damage from a 0.635-cm Pyrex projectile impacting into a 1.27-cm (2a) ice layer over PMMA target. Impact velocity: 5.4 km/s, impact angle: 30° from the horizontal. (middle) Corresponding CTH calculation showing plastic strain. Failure occurs at 10% plastic strain, which is marked by a black line on the colorbar and is outlined by a black contour in the images. (right) Corresponding pressure contours. Positive values and warm colors indicate compression, while negative values and cold colors indicate tension.

Figure 9. Plastic strain at 50 μ sec after impact for laboratory-scale simulations of four different target geometries. All impacts were at 30° above the horizontal and 5 km/s. Strain to failure set at 10%. a) No layer, impact directly into PMMA surface; b) impact into 1-projectile-diameter (0.635 cm) thick ice layer on top of PMMA surface; c) impact into 1-projectile-diameter (0.635 cm) thick Plasticine layer on top of PMMA surface; d) impact into 2-projectile-diameter (1.27 cm) thick ice layer on top of PMMA surface. Surface layers shield the underlying substrate, resulting in reduced overall damage and crater size. Initial projectile size and trajectory arrow are shown for reference.

Figure 10. Peak pressure with depth for the four different model geometries seen in Figure 8. All four models were for a 0.635-cm Pyrex projectile impacting at 5 km/s and 30° above the horizontal. (top) Peak pressure with depth, directly below the impact point. (middle) Peak pressure with depth 1 cm downrange from the impact point. (bottom) Peak pressure with depth 2 cm downrange from the impact point.

Figure 11. Planetary scale models showing pressure contours at 1 second after impact. Projectile: 1-km dunite sphere, Impact angle: 30° , Impact velocity: 15 km/s. Projectile size is shown for comparison. Three different cases are shown: (left) Impact directly into basaltic substrate, (middle) Impact into 1-km thick sedimentary layer over basaltic substrate, (right) Impact into 1-km thick ice layer over basaltic substrate.

Figure 12. Schematic locations of selected Eulerian tracer particles within large-scale layered and unlayered CTH models.

Figure 13. Pressure decay for large-scale CTH models of layered and unlayered targets. Three cases are examined: 1) 1-km dunite sphere impacting into basalt target; 2) 1-km dunite sphere impacting into a 1-km thick sediment layer overlying basaltic bedrock; and 3) 1-km dunite sphere impacting into a 1-km thick ice layer over basaltic bedrock. All three impacts were at 30° and 15 km/s. a and b) Peak pressure with distance from the impact points for each case; c) pressure with time for each case. Surface layers delay the arrival of the shock wave, and significantly reduce the peak pressure. d) Peak pressure with depth, 1 km downrange from the impact point. Peak pressures are higher downrange than directly below the impact point for oblique impacts. Note that the vertical dashed line shows the depth of the basalt-layer interface.

Figure 14. Strain contours for 1-km impact into three separate geometries described in Figure 10. The substrate surfaces are shown at an equal elevation here, and the 1a-thick surface layer and approximate crater size at 1 sec after impact have been masked to show what the subsurface might “look like” following post-impact erosion. The dashed line indicates the depth of the crater for an impact directly into basalt. a) Impact directly into basalt; b) impact into a 1-km thick sediment layer over basalt; c) impact into a 1-km thick ice layer over basalt; d) vertical impact directly into basalt; e) vertical impact into 1-km thick sediment layer over basalt; f) vertical impact into 1-km thick ice layer over basalt. Though the surface layers provide some shielding at high impact angles, resulting in shallower crater depths, the effect of the low-impedance surface layer is more pronounced for oblique impacts.

Figure 15. Internal energy partitioning following impact into a 1.27-cm Plasticine layer. Projectile: 0.635-cm Pyrex sphere, impact angle: 30° , impact velocity: 5.45 km/s; 1:1 comparison to AVGR experiment #110107. Approximately 70% of the energy is coupled into the surface layer, while only $\sim 10\%$ is transmitted into the PMMA substrate.

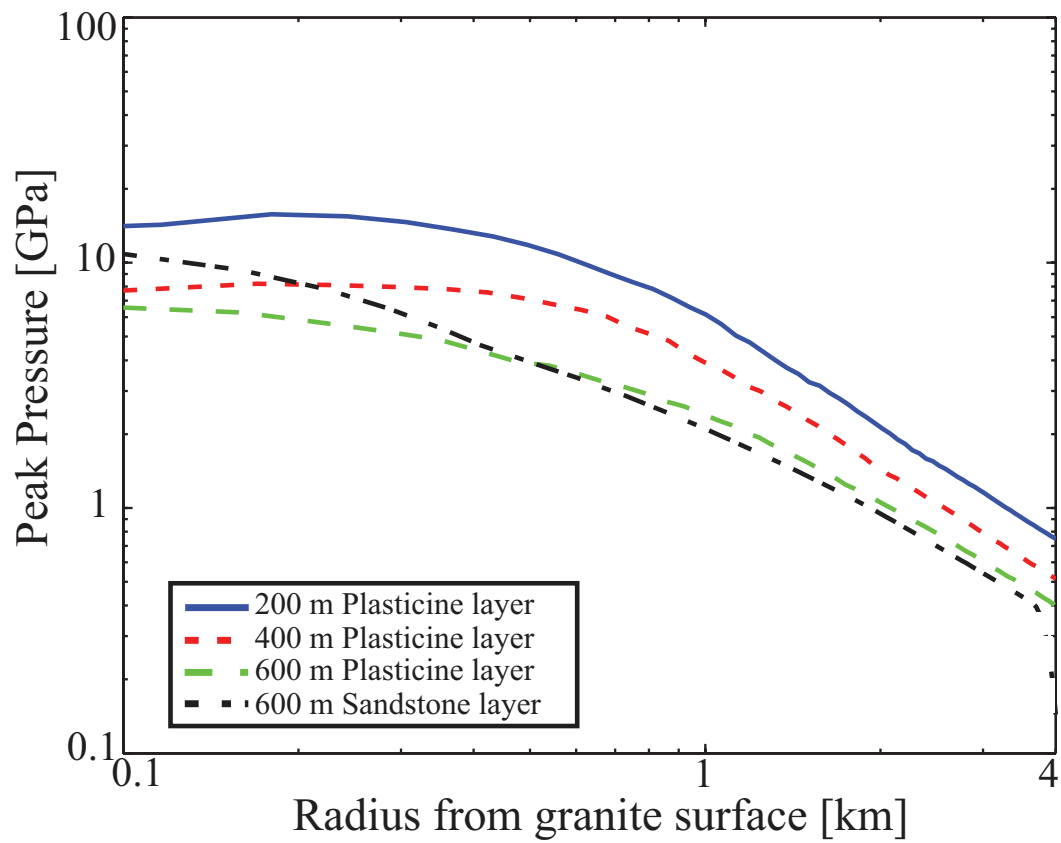


Figure 1

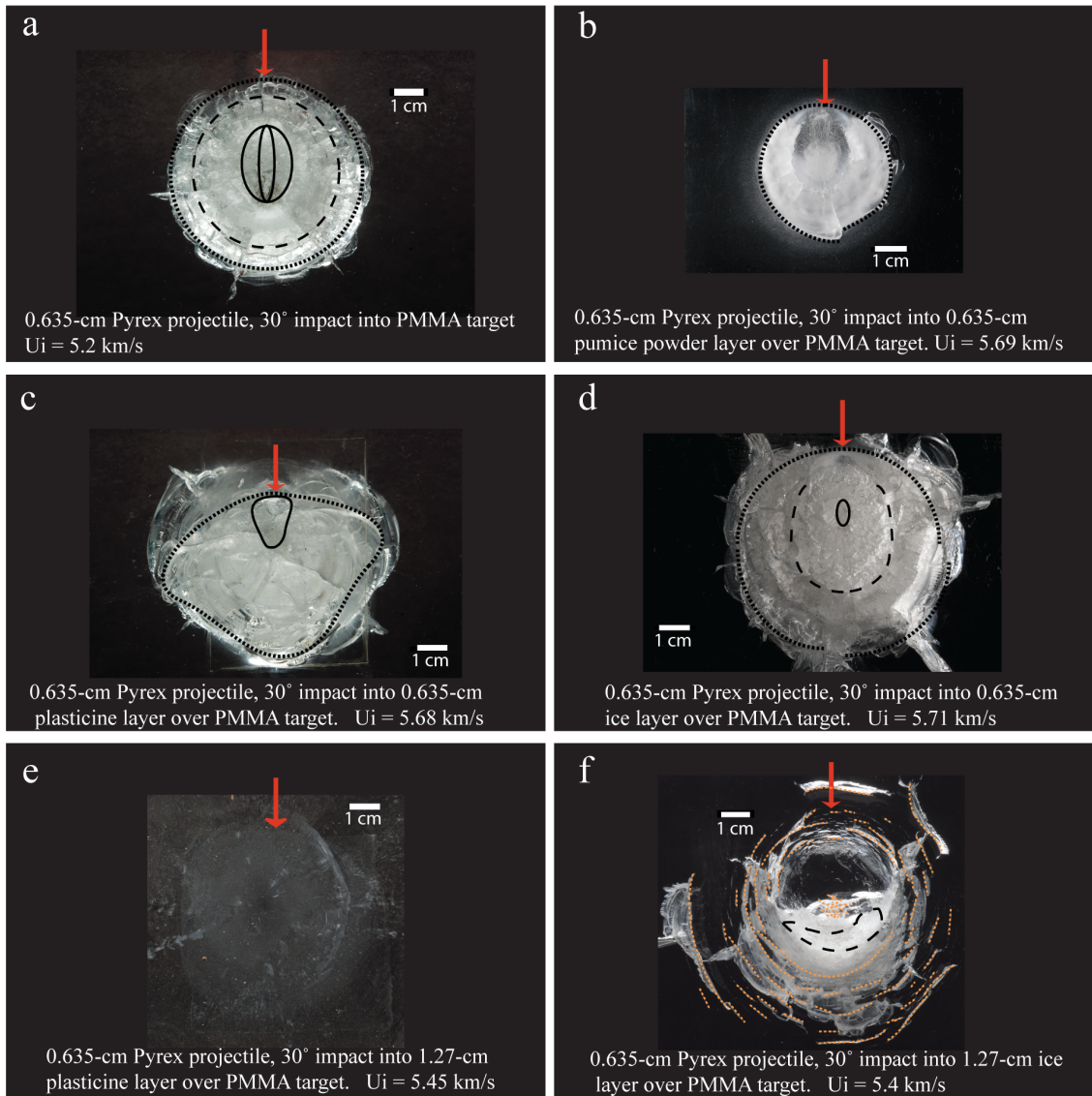


Figure 2

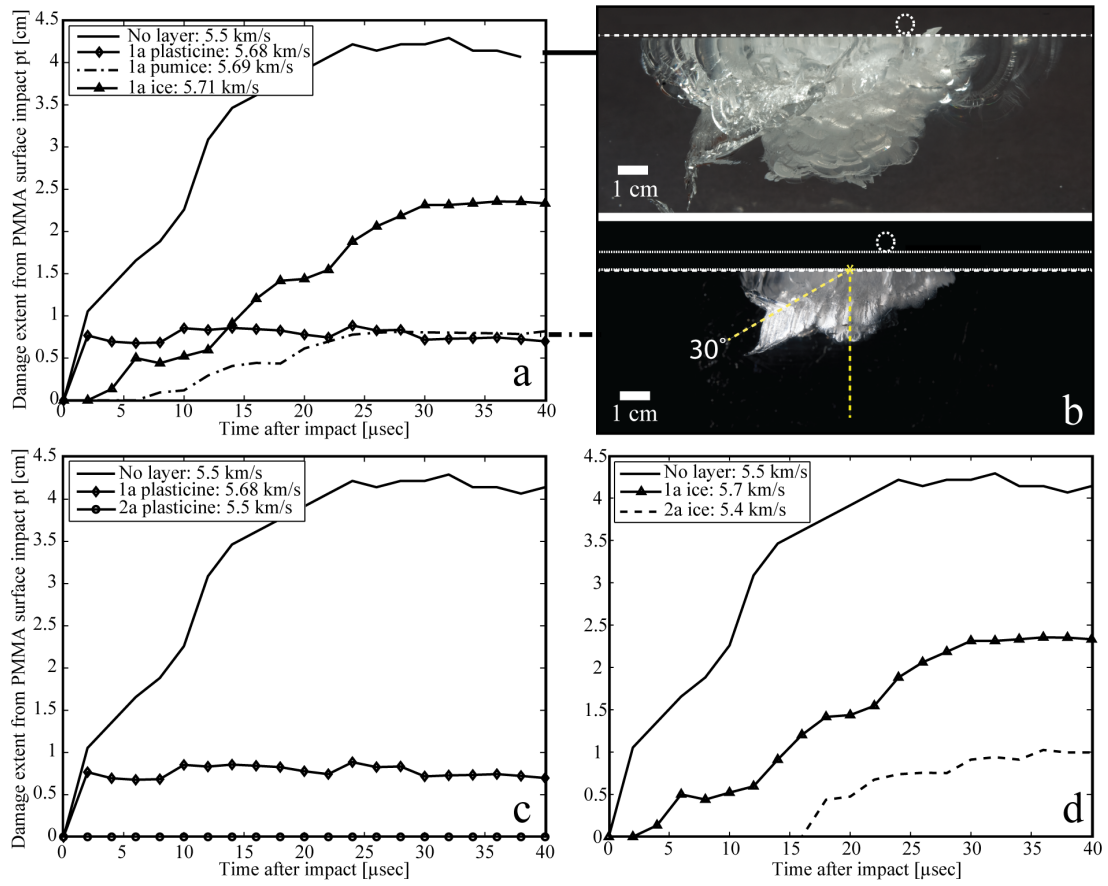


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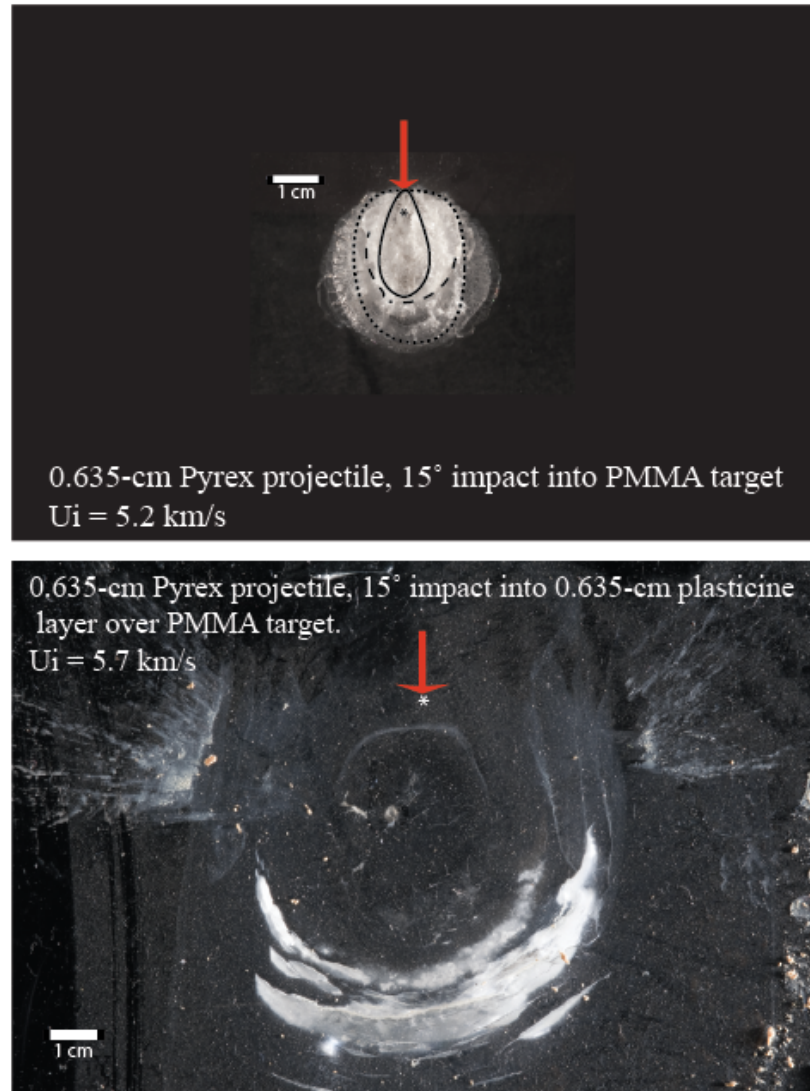


Figure 4

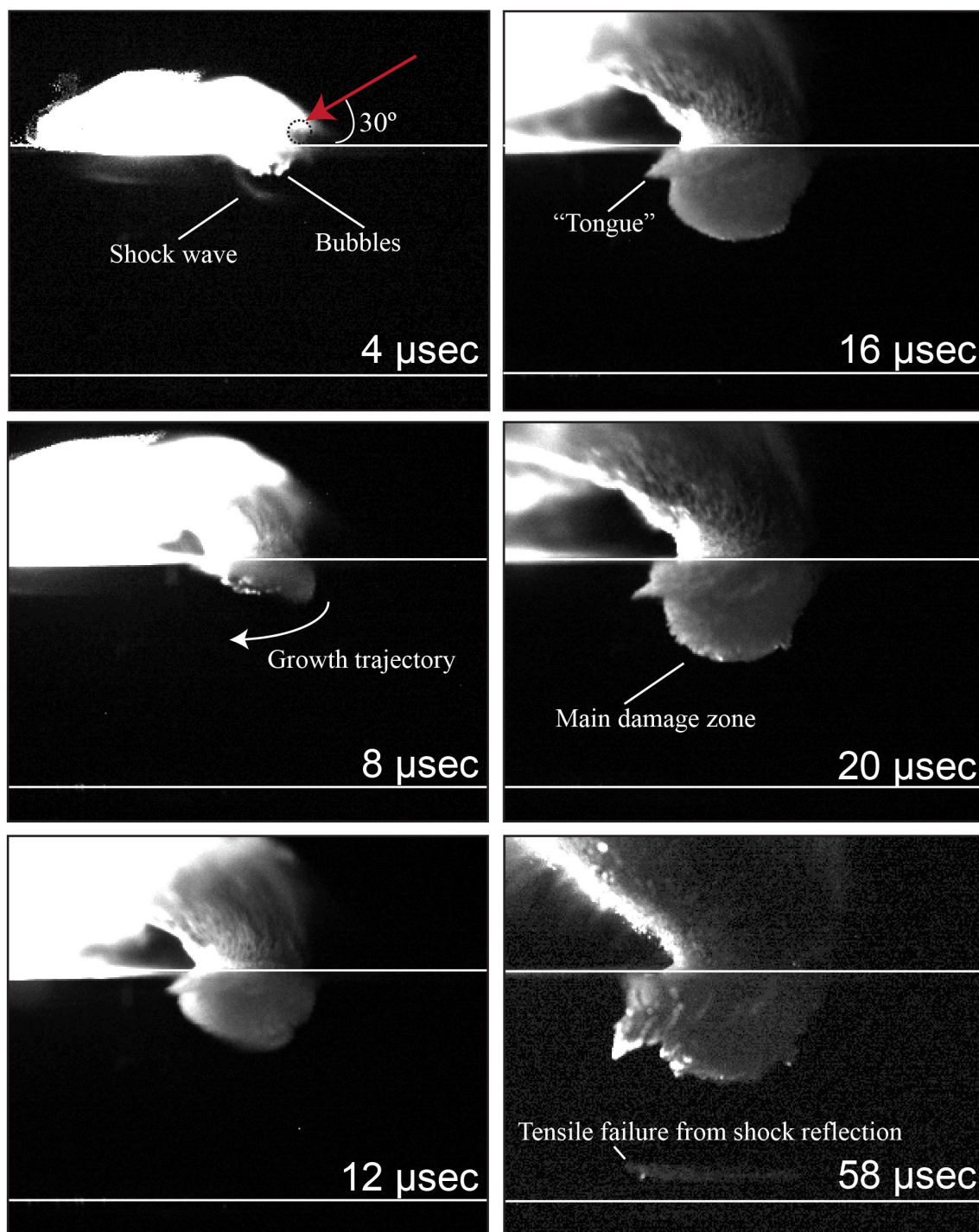


Figure 5

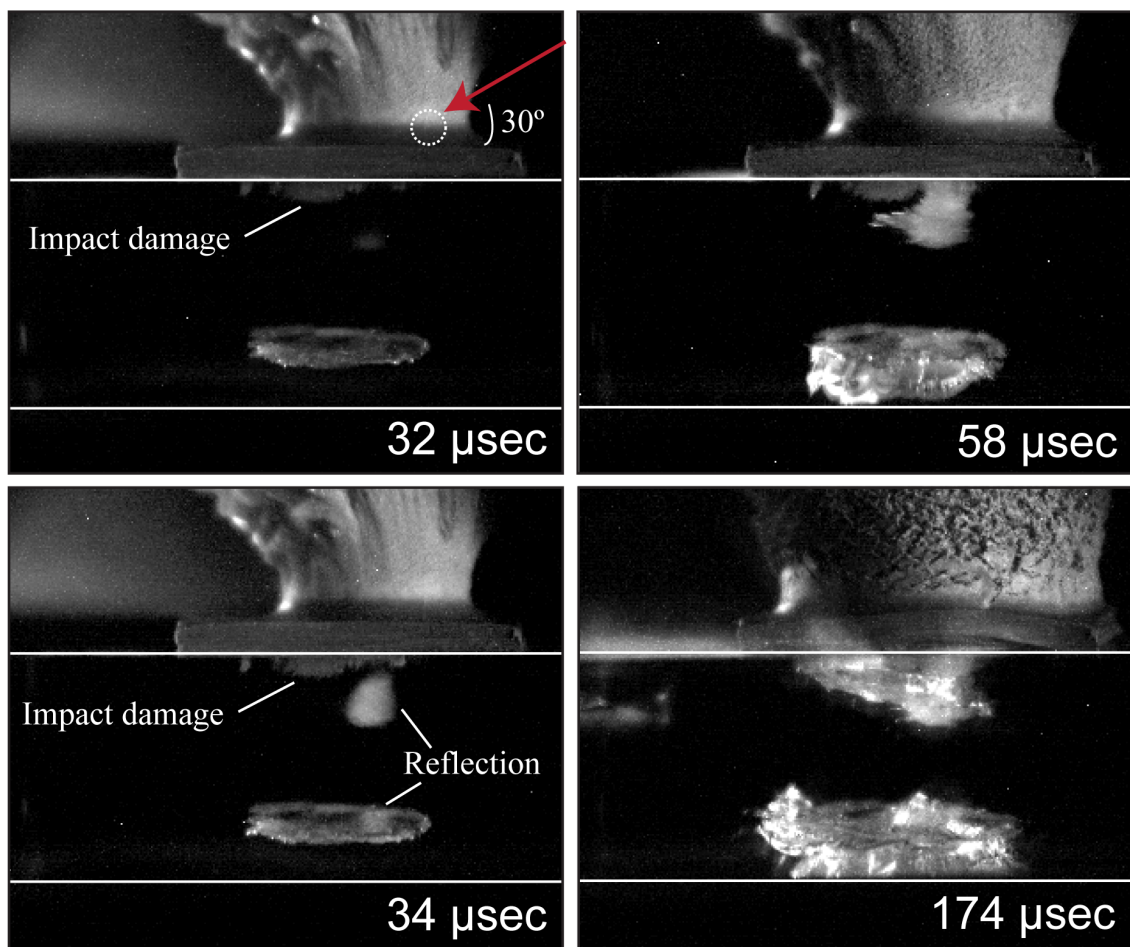


Figure 6

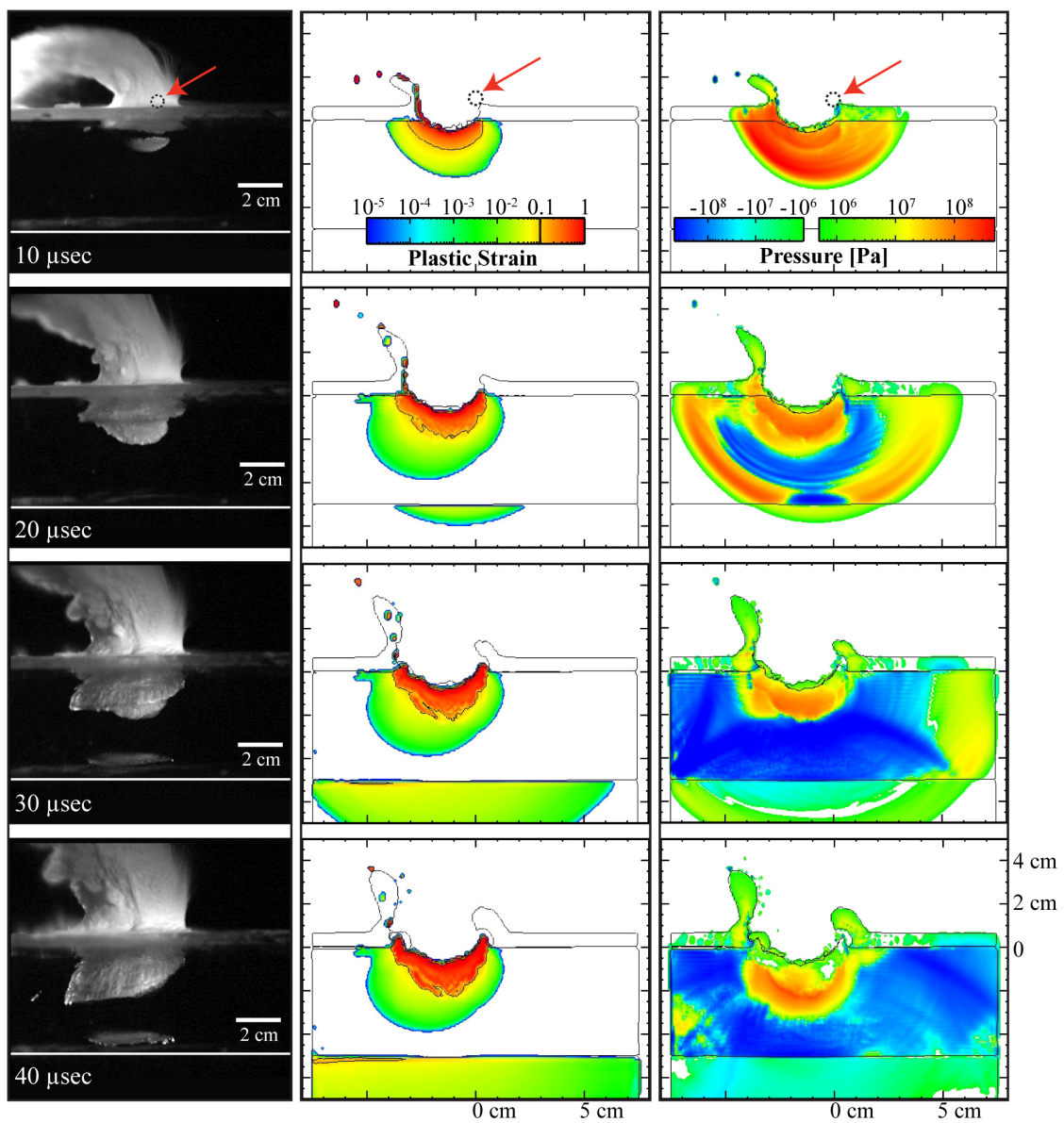


Figure 7

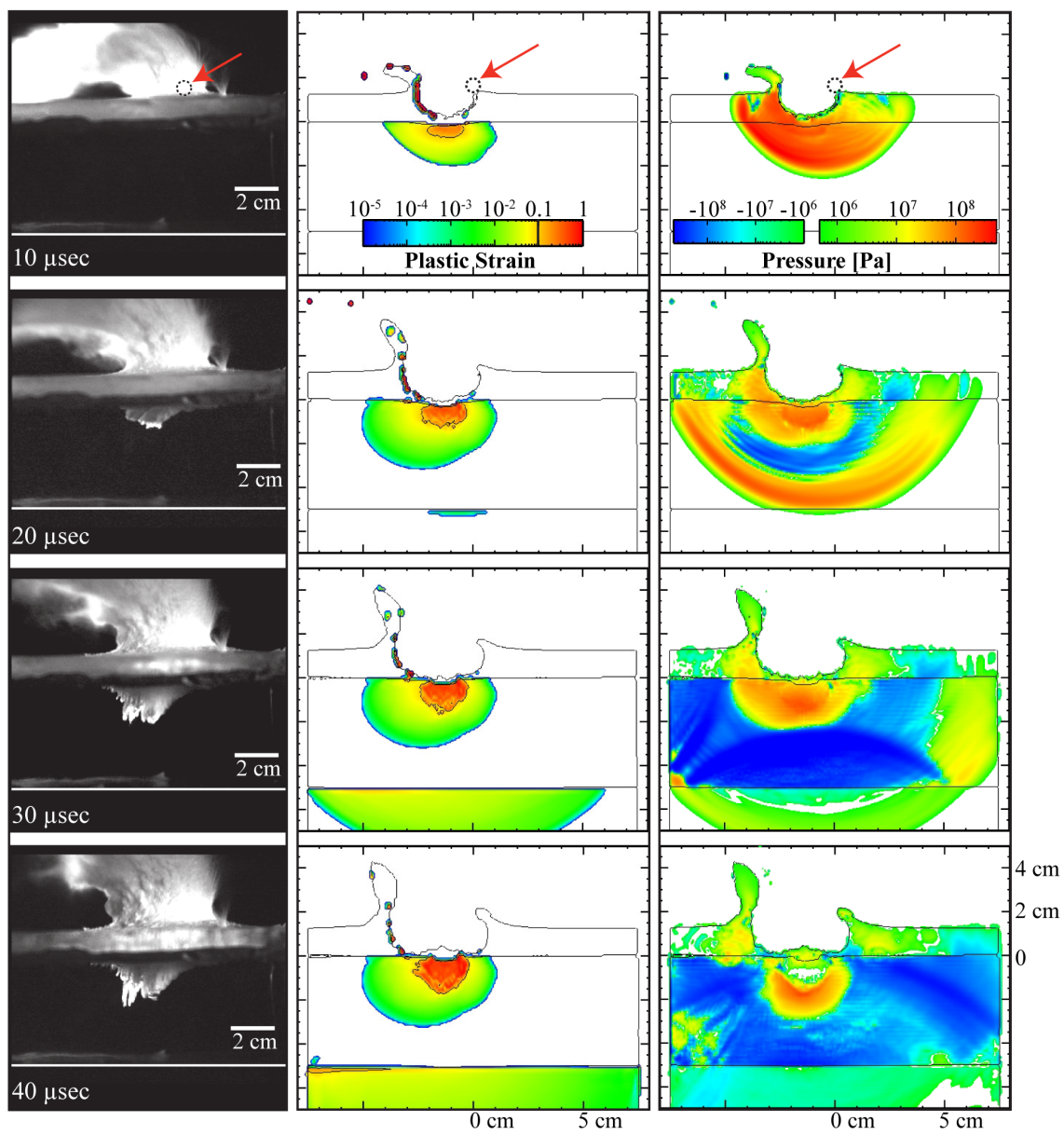


Figure 8

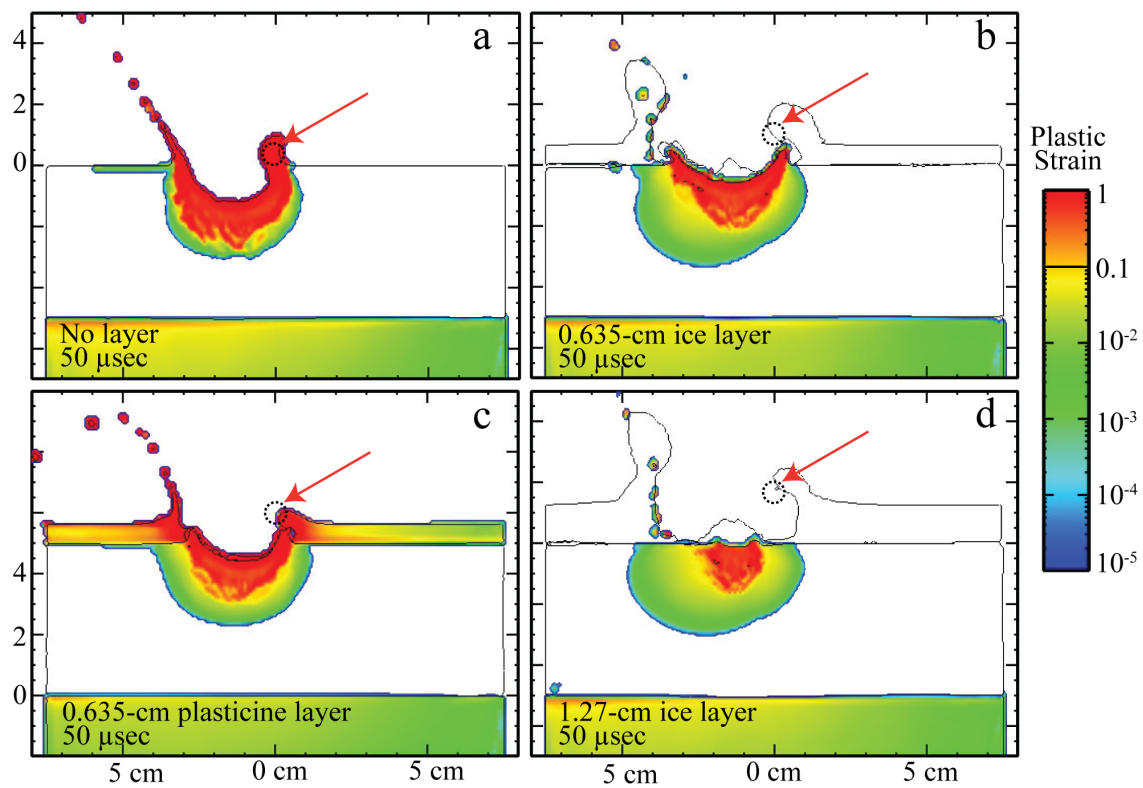


Figure 9

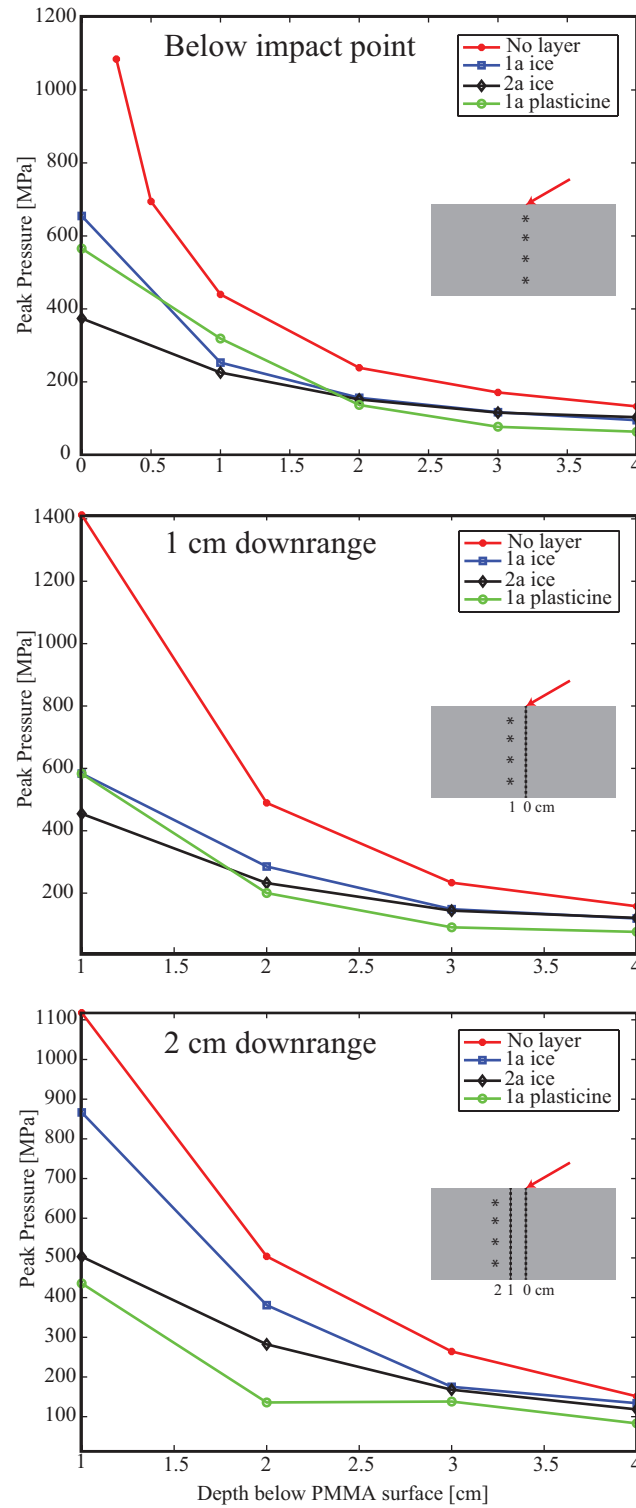


Figure 10

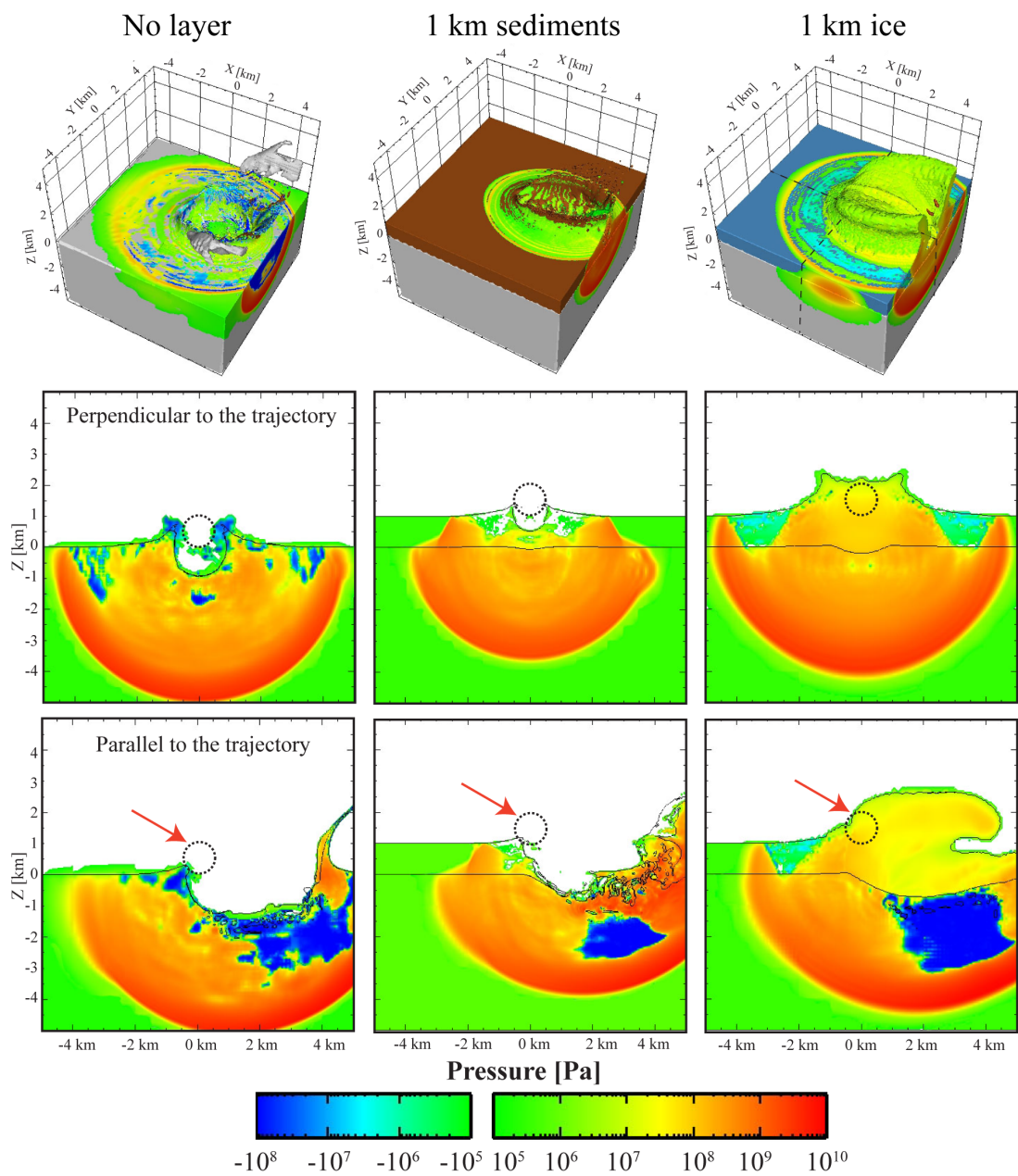


Figure 11

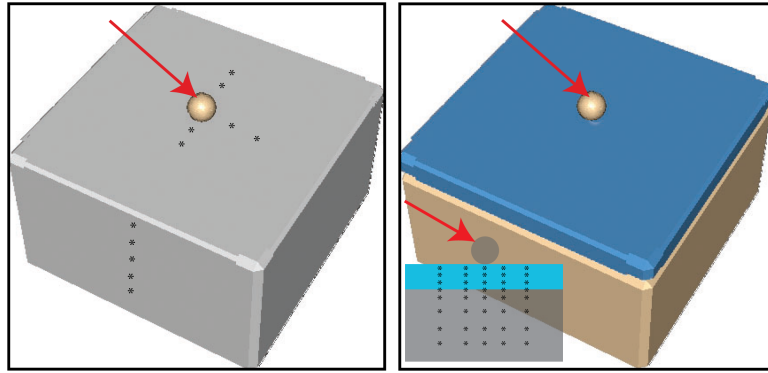


Figure 12

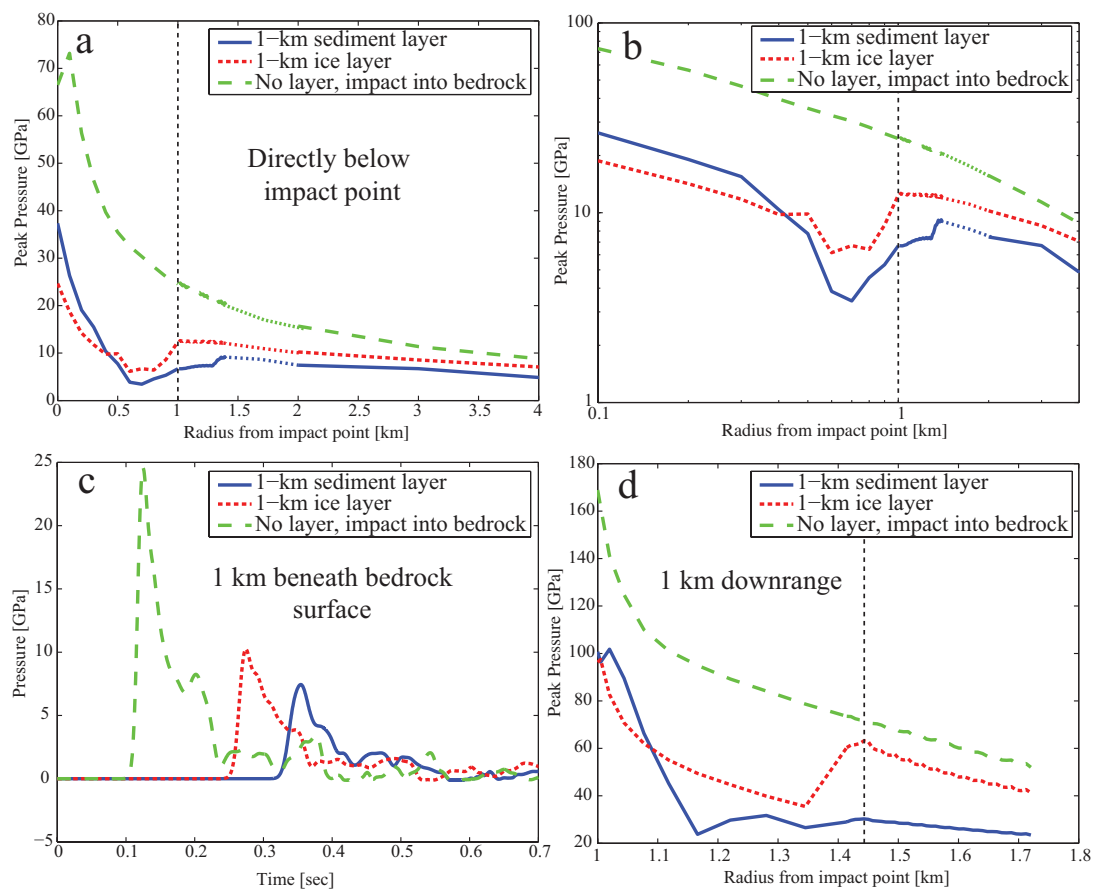


Figure 13

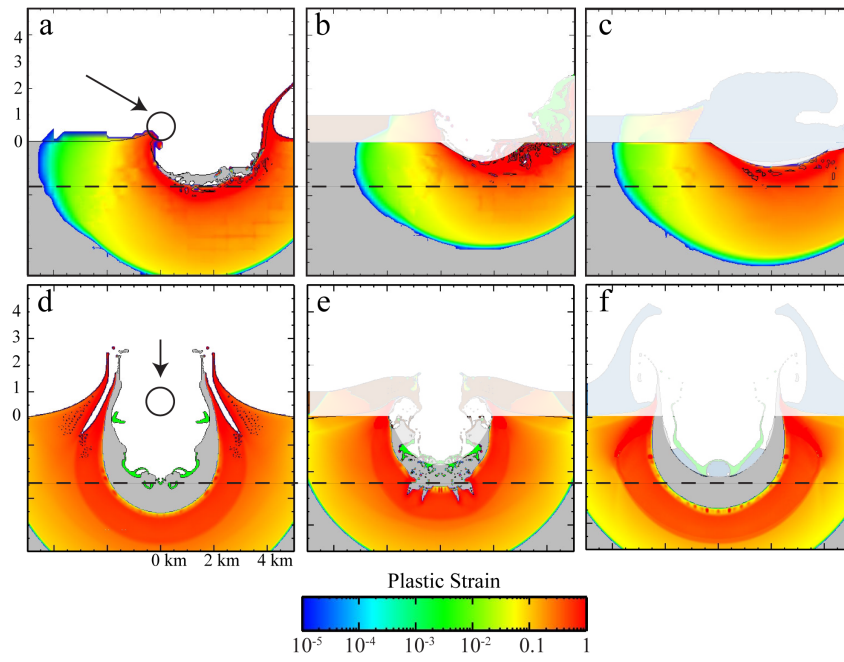


Figure 14

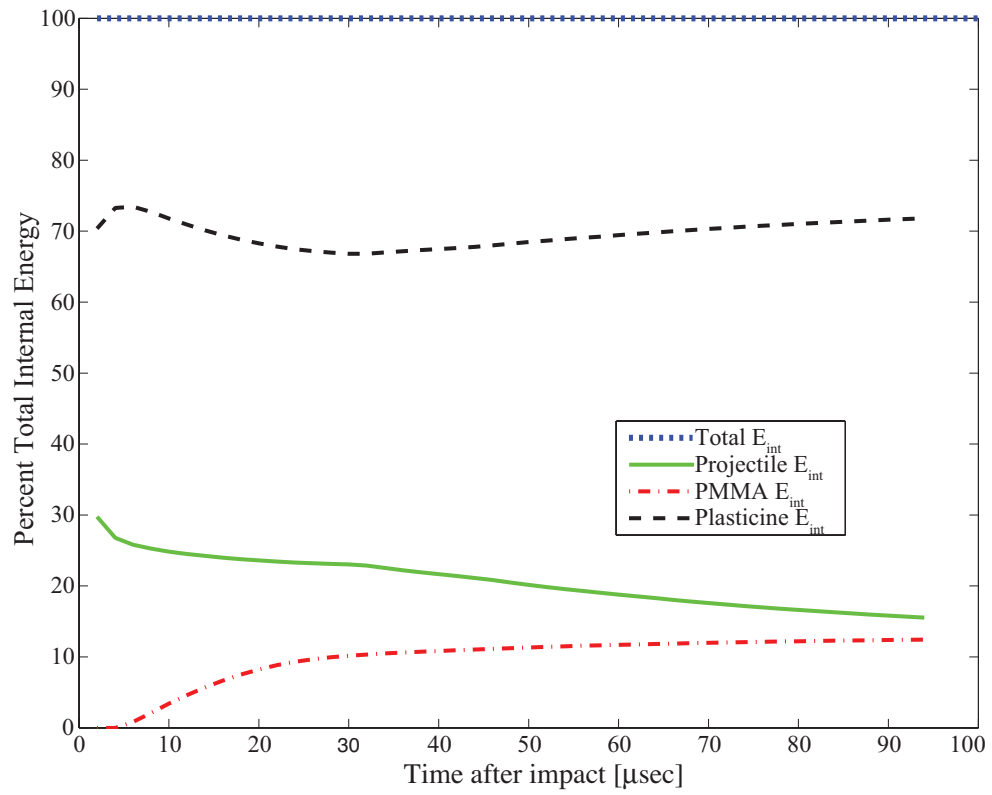


Figure 15

Chapter 4

Investigating pressure magnitudes at depth for oblique impacts into layered targets: Applications to terrestrial impacts in sedimentary targets

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Abstract - Low-impedance surface layers over high-impedance bedrock affect energy coupling and shock effects in the substrate. The Rock Elm impact structure in Wisconsin (USA) and the Upheaval Dome in Utah (USA) illustrate this process. In both cases, removal of surface sediments erased most of the original impact structures, thereby making identification of the impact origin difficult. In this study, a combination of laboratory and 3D numerical experiments reveals the underlying processes controlling subsurface deformation and demonstrates that a low-impedance layer can reduce expression of peak shock pressures left in the rock record, as at the Rock Elm and the Upheaval Dome impact sites. 3D-CTH models of the Rock Elm impact structure predict that peak shock pressures should fall below the HEL of quartz in the basement rocks yet still induce permanent deformation. The model predicts peak pressures around 5-10 GPa, levels consistent with field observations of shocked quartz from both Rock Elm and the Upheaval Dome. Consequently, other impact sites exhibiting minimal shock features might be explained.

INTRODUCTION

Planetary surfaces often present layered targets. In particular, sediments cover much of the Earth. A low-impedance layer (sediments, or even ice) over a high-impedance layer (crystalline bedrock) can affect energy coupling and shock effects in the substrate [Stickle and Schultz, 2011a]. Two specific terrestrial craters illustrate the effects of layered targets: the Rock Elm impact structure in Wisconsin (USA) and the Upheaval Dome in Utah (USA).

The Rock Elm impact structure formed in approximately 500-600 m thick sediments overlying crystalline basement rock [French *et al.*, 2004]. The impact created a crater approximately 7.5 km in diameter with a central uplift and final depth of 400 m. Over time, approximately half of the overlying sediment layer (roughly 300 m) has been eroded, leaving behind a muted depression ~6.5 km wide. Weakly shocked quartz grains within the central uplifted crystalline basement exhibit evidence of only low-level shock pressures, i.e., on the order of 5-10 GPa [French *et al.*, 2004].

The Upheaval Dome in Utah resembles the Rock Elm structure in that unequivocal evidence for shock effects remained illusive for many years [French and Koeberl, 2010]. Even though the Upheaval Dome occurs in an area of highly deformed rocks, shocked quartz grains were not discovered until relatively recently [Buchner and Kenkmann, 2008]. As a result, earlier studies proposed a range of hypotheses for its origin, including: cryptovolcanism [Bucher, 1936], impact [e.g., Kriens *et al.*, 1999; Kenkmann, 2003; Kenkmann *et al.*, 2005; Scherler *et al.*, 2006; Okubo and Schultz, 2007] and salt diapirism [e.g., Jackson *et al.*, 1998].

In the cases of both Rock Elm and the Upheaval Dome, removal of surface sediments made identification of the impact structure more difficult by erasing obvious mineralogic signatures. Both examples represent areas of highly deformed rocks without ubiquitous shock features (only scattered weakly shocked minerals). As a result, their origin has been debated [e.g., Bucher, 1936; Cordua, 1985; Jackson, 1998]. This study, therefore, focuses on the observable metrics left behind by an oblique impact into a layered target. Here we will assess: (a) types of deformation expected in layered targets; (b) the effect of a low-impedance surface layer on this deformation; (c) shock effects in

the substrate; and (d) expectations for impact evidence following removal of the overlying sediments. Specific, measurable quantities include subsurface deformation and peak shock pressure at depth. Laboratory experiments provide a context for these studies, whereas numerical models reveal pressure evolution and specific comparisons to field studies at the Rock Elm impact structure [French *et al.*, 2004] and the Upheaval Dome [Buchner and Kenkmann, 2008].

EXPERIMENTAL APPROACH

The combination of laboratory and 3D numerical experiments reveals important information about the underlying processes controlling subsurface conditions. For these experiments, subsurface damage can be easily visualized and tracked through the use of transparent targets. Impact conditions, (e.g., impact angle, velocity, and target structure) affect extent and styles of damage, and varying these parameters provides insights into the physical processes following oblique impacts. Such experiments also provide an important benchmark for laboratory-scale numerical models [e.g., Pierazzo *et al.*, 2008; Stickle and Schultz, 2011b], and an essential reality check for complicated material models. The numerical models also provide critical insights into the cratering process as well as the modes of failure. Three-dimensional CTH models are used here to 1) compare with experimental data, and 2) examine how the small-scale processes found in laboratory experiments and laboratory-scale simulations are manifested at large scale. Such a strategy can be used to reveal underlying physical processes that may be difficult to determine from the experiments alone.

Laboratory Experiments

Laboratory experiments were performed at the NASA Ames Vertical Gun Range (AVGR) at the Ames Research Center in Mountain View, California. The AVGR's two-stage light gas gun achieves impact velocities from 3-7 km/s at impact angles from 15-90° above the horizontal. The target chamber is a 2.5-m diameter vacuum chamber that can accommodate a variety experimental designs and target types. In this study, 15 x 15-cm planar polymethylmethacrylate (PMMA) targets, with thicknesses ranging from 5-6.35 cm were used. Layers of pumice, ice or Plasticine were added to the top of these blocks in order to observe the effects of a low-impedance layer on the distribution and type of damage in the substrate. The surface layer thickness ranged from 0.635-1.27 cm (1-2 projectile diameters). In order to create the composite targets, Plasticine was pressed on top of the PMMA, ice was frozen onto the PMMA overnight and powdered pumice was poured onto the block surface. Each target was placed on a Styrofoam block within the target chamber, which minimizes free-surface effects following impact. PMMA turns opaque when damaged; thus, this target reveals the subsurface damage more easily. Experimental studies have shown that PMMA is brittle at high strain rates and room temperature, thus it can be used as a laboratory analog to brittle rocks at the surface of the planets [e.g., de Joussineau *et al.*, 2003; Rosakis *et al.*, 1999; Rosakis, 2002; Rosakis *et al.*, 2004; Rosakis *et al.*, 2008; Rittel and Brill, 2008; Misra *et al.*, 2009; Nasraoui *et al.*, 2012].

Spherical Pyrex projectiles with a diameter of 0.635 cm impacted the targets with velocities ranging from 3.5-6.4 km/s at an angle of 30° above the horizontal. Two high-speed cameras (Shimadzu, HV-1) recorded the evolution of the subsurface damage over

the first 100-200 μs after impact. A frame rate of 500,000 frames per second provides sufficient time resolution to track the rate of damage growth and the evolution of damage regions.

Numerical Models

CTH is a multi-dimension, multi-material, two-step Eulerian hydrocode developed by Sandia National Laboratories in Albuquerque, NM [McGlaun *et al.*, 1990] and is used widely in simulations of hypervelocity impacts and, more specifically, has been used to study impacts into layered surfaces [for example, Pierazzo and Melosh, 1999; Collins, *et al.*, 2008; Pierazzo *et al.* 2008; Senft and Stewart, 2007, 2008]. The code is designed to model strong shock, large deformation processes. In addition, a wide variety of equations of state (EOS) and material models are available.

All calculations are performed in a 3D rectangular coordinate system, which allows oblique impacts to be studied in detail. The Mie-Grüneisen equation of state (EOS) is used for Pyrex [Marsh, 1980], PMMA and Styrofoam blocks (both are available within the CTH package, and laboratory coefficients are used) and Plasticine layers [Thomsen *et al.*, 1979] while the semi-analytical ANEOS EOS [Thompson and Lauson, 1984; Thompson, 1990] is used to model the ice layers. Table 1 details Mie-Grüneisen EOS parameters used in these models.

Accurately modeling damage and deformation requires sophisticated constitutive models to approximate observed behavior of materials undergoing differential stress. The Pyrex projectile is assumed to behave like a geologic material, and thus we used a pressure-dependent yield surface as a failure model. A slightly more complicated failure model tracks damage within the subsurface in the small-scale CTH models. The

Johnson-Cook Fracture (JCF) model illustrates regions of plastic failure (or regions undergoing shear deformation) within the PMMA substrate. The JCF model is a scalar damage model used to predict failure of material due to equivalent plastic strain as a function of pressure, temperature, strain rate and loading path [Johnson and Cook, 1985]. A scalar damage parameter, D , is calculated in each cell that ranges from 0 (pristine, undamaged material) to 1 (fully damaged material). Failure occurs when $D=1$. This damage parameter is calculated as:

$$\frac{dD}{dt} = \frac{\dot{E}}{E_F} \quad (1)$$

where $\dot{E}$ is the equivalent plastic strain rate and E_F is the local value of strain to fracture, which is calculated by:

$$E_F = (D_1 + D_2 \exp\left(\frac{-D_3 p}{Y}\right)) * (1 + D_4 \ln(\dot{E})) * (1 + D_5 T_{hom}) \quad (2)$$

where D_1 - D_5 are constants, p is pressure, Y is the local yield stress and T_{hom} is the homologous temperature, defined by:

$$T_{hom} = \frac{T - T_{room}}{T_M - T_{room}} \quad (3)$$

where T_M is the melting temperature of the material. Once the material has failed, the yield strength is then assumed to be zero within the failed region. To minimize the parameter space, plastic strain (represented by D_1 in equation (2)) is the only variable considered: shear failure will occur when the material experiences stresses greater than the yield strength and then undergoes plastic strain. Failure thus occurs at a user-specified value of plastic strain; here, we assume failure occurs at 10% plastic strain

(based on comparisons with target damage experiments) with constants D_2 - D_5 assumed to be zero. A parameter study comparing numerical results to experimental observations determined appropriate values for D_1 and the yield strength of PMMA [Stickle and Schultz, 2011b]. The PMMA is assumed to have a yield strength of 120 MPa. The Plasticine is modeled using a pressure dependent von Mises strength model [after Christensen *et al.*, 1968, Thomsen *et al.*, 1979, and Austin *et al.*, 1980], while ice surface layers are treated as a geologic material and modeled using a pressure-dependent strength model [after Gold, 1977].

Simulations also replicated conditions at much larger scale, specifically the Rock Elm impact structure [following French *et al.*, 2004]. Prior to the impact, the target site had a sedimentary layer overlying a granitic basement. Three separate cases were examined: layers with thicknesses of 200 m, 400 m, or 600 m (1a-2a, where a is the projectile diameter) with a 200-m diameter dunite sphere as the projectile. The impact velocity is 30 km/s at two different impact angles, 30° and 45° above the horizontal. The Adaptive Mesh Refinement (AMR) routine [McGlaun *et al.*, 1990; Crawford, 1999] automatically refines the mesh around regions of high pressure (i.e., the shock wave) so that the resolution varies throughout the entire domain, with a lower resolution far from the impact point. AMR significantly reduces computational time. The maximum resolution for these models was 15 m, or ~13 cells across the projectile diameter. A study performed by Pierazzo [2006] showed that resolutions similar to those considered here will result in an underestimation of the peak pressure in a 3D simulation by ~10% compared to high-resolution 3D simulations (high-resolution is defined as ~20 cells per projectile radius). This difference is small enough that the conclusions of this paper are

essentially unchanged, and the models in this study are run at significantly high resolution to track pressure decay in the substrate. Granite, dunite and ice were modeled as geologic materials with a pressure-dependent yield surface and the ANEOS EOS. The surface sedimentary layer was modeled as Plasticine with a Mie-Grüneisen EOS [after Thomsen *et al.*, 1979] and the same von Mises strength model used in the laboratory-scale models. Table 2 summarizes material parameters for these models. Plasticine was chosen as a proxy for sedimentary material for two reasons. First, it provides a more direct comparison to the laboratory models. Second, the acoustic impedance (defined as the product of the uncompressed density and the sound speed) of Plasticine resembles the impedance of a sedimentary layer (Table 2).

RESULTS

Laboratory experiments provide context for numerical studies (described below). An impact into a target with a low-impedance surface layer significantly modifies the evolution, extent, and pattern of failure in the substrate. Figure 1 illustrates these differences, including damage evolution for three different target geometries: a) impact directly into PMMA; b) impact into a 1-projectile-diameter (1a) thick pumice layer over PMMA; and c) impact into a 1a-thick ice layer over PMMA. All three impacts used a 0.635-cm spherical Pyrex projectile impacting at ~5.6 km/s (impact angle of 30° above horizontal).

Three general damage regions characterize each experiment: the central, primary damage region (indicated by a white arrow in Fig. 1), a diving “tongue” of damage downrange from the impact point (indicated by a curved yellow arrow in Fig. 1), and

extensional failure at the base of the target due to shock wave reflection off the free surface. The surface layer affects the central damage region the greatest. As the surface layer thickness increases, both crater size and extent of damage below reduce. Moreover, onset of subsurface damage formation begins later and the pattern of failure changes. For example, no damage occurs in the substrate for a thick (2a) surface layer of ice or Plasticine. Consequently, the presence of a low-impedance surface layer drastically reduces the amount and evolution of damage present in the substrate.

The small-scale experiments raise the possibility that reduced substrate damage also could occur at much larger scales. For illustration, formation of the terrestrial crater in the Rock Elm region, USA, was modeled using pre-impact lithologies described by French *et al.* (2004). Here, two different impact angles were examined in detail, each with three separate target geometries. For a nominal impact angle of 45° , a 200-m (1a) stony meteorite was assumed to impact at 30 km/s [French *et al.*, 2004]. This led to the formation of a transient crater about 4 km wide and 1.3 km deep. Fig. 2 shows three models with geometries expected to be similar to the initial Rock Elm stratigraphy. The approximate transient crater depth, width and final crater width are shown for scale. French *et al.* [2004] assumed that 600 m of sediments originally covered granite basement. In this study, three different layer thicknesses, 200 m (Fig. 2a), 400 m (Fig. 2b) and 600 m (Fig. 2c) were examined in order to characterize the effect of layer thickness on the process and final materials in the crater. A thin surface layer resulted in the largest crater, as might be expected from the experimental results. At the same time after impact, a thicker surface layer, however, resulted in a broader pressure front within the substrate. After the transient crater reached its maximum depth (about 0.9 seconds

after impact), shocked materials beneath the crater floor would not have been ejected. Consequently, comparisons can be made between the peak pressures recorded in model and the rock record.

Eulerian tracer particles throughout the target track the evolving pressure and strain at different depths below the granite-sediment interface (Fig. 3). The peak pressure decreases significantly with depth, and exceeds the assumed Hugoniot Elastic Limit (HEL) of quartz only in the case of a 200-m thick surface layer. The 400-m thick layer resulted in a double pressure front, also evident but less pronounced with the 600-m thick layer. At the sediment-granite interface, peak pressures greatly exceed those at depth (~3X higher in the 200 m layer case). Since materials near the interface will be ejected from the crater, they are not considered here.

Impact angle affects how energy and momentum are coupled to the target [e.g., Gault and Wedekind, 1978; Schultz and Gault, 1990a, 1990b; Pierazzo and Melosh, 1999; Dahl and Schultz, 2001]. While 45° is the nominal impact angle [Gilbert, 1893; Shoemaker, 1962], half of all planetary impacts will be below this value; consequently, CTH computations also examined the effect of impact angle. A 30° impact with the same model geometries as in Fig. 2 results in a larger but shallower crater with smaller peak pressures at the same time after impact (Fig. 4). Peak pressures in the basement rocks remain below the HEL of quartz in all three cases, even at a depth of 1 km directly below the impact point (Fig. 5).

The model reveals that material should have been ejected or displaced downward and downrange down to a depth of 1 km for both 30° and 45° cases directly below the impact point, beginning at the layer-granite interface (Fig. 6). Above a depth of 1 km, the

most highly shocked material is ejected. Below 1 km, most of the material subjected to low shock pressures remains within crater. Only a small region of material would have experienced sufficiently high peak pressures to leave behind diagnostic shock features (e.g., the HEL limit for shocked quartz is at 5 GPa).

DISCUSSION

Stratigraphy of the pre-impact surface should affect the final crater size and structure, as well as the distribution of shocked states. Even a thin layer, on the order of the projectile diameter (1a), can act to shield the competent substrate enough to reduce peak pressures from an oblique impact by 60-70%. Numerical models also show that the pressure waves tend to be guided along the surface layer downrange, further reducing the magnitude of pressure wave transmitted into the substrate. If the layer is on the order of two to three projectile diameters, it is possible that a relict crater may not contain significant shocked material yet still exhibit substantial subsurface strain and deformation. Here, numerical models predict peak pressure magnitudes within the bedrock beneath the impact point of 6 GPa for a 200 m thick sedimentary layer over granite bedrock. Peak pressure drops significantly as the layer thickness increases and with distance from the impact point. The more heavily shocked materials will be difficult to sample in the field (unless exposed by erosion or cored) since they occur at the base of the breccia lens.

Similarly, the exact point of impact cannot yet be easily established in the field. Instead, shock effects are referenced to the final crater geometry. In our models, the final crater (after modification) is estimated to be 6.5 km in diameter. Below the granite-

sediment interface, the peak-shock state depends on location. For example, the crater center is actually ~2 km downrange from the impact (Fig. 7). Most material at depth surrounding the crater center had been shocked to only low pressures (Fig. 8). The only material left in the crater with identifiable (although weak) shock effects occurs uprange from the impact point, close to the crater center (Fig. 8a). Materials below and downrange of the crater center (Fig. 8b and 8c) should exhibit peak pressures well below the HEL of quartz. These figures can also be used to determine the far-field pressure attenuation rate [Ahrens and O'Keefe, 1977], as shown in Tables 1 and 2 for the different target geometries at 45° and 30°, respectively.

The models described here provide important clues into what might be found within impact craters in regions originally covered by layered sequences. For example, finding highly shocked material within the existing structures at both the Rock Elm and the Upheaval Dome impact sites is made more difficult by the shielding from, and erosion of, the surface layer. Based on results of the model, materials with the greatest shock states should occur downrange of (but near to) the impact point, which is now likely uprange of the crater center. Relatively little of the most-highly shocked material, however, will remain within the substrate of the relict crater because so much energy is coupled to the surface layer.

Many terrestrial craters occur in sedimentary material [Grieve and Robertson, 1979]. One example, the Upheaval Dome, has been extensively mapped and studied [e.g., Bucher, 1936; McKnight, 1940; Jackson *et al.*, 1998; Kriens *et al.*, 1999; Kenkmann, 2003; Kenkmann *et al.*, 2005; Scherler *et al.*, 2006; Okubo and Schultz, 2007]. Kenkmann and Scherler [2002] interpreted the structural deformation as evidence for an

oblique impact from the WNW with the central uplift shifted downrange somewhat. An oblique impact would further reduce the peak pressures expected in the substrate as the surface sedimentary layer guides the shock wave along the interface, minimizing the energy coupled to the substrate [Stickle and Schultz, 2011a]. Any material experiencing high enough peak pressures to form shock features (i.e., shatter cones or planar deformation features) would then be expected downrange from the impact point, near the crater center. In a detailed mapping study arguing for impact origin of the Upheaval Dome, Kriens *et al.* [1999] discovered shatter cones and planar microstructures in quartz grains in the Moenkopi Formation and White Rim Sandstone near the center of the Upheaval Dome. This location is consistent with the predictions of our models. Nevertheless, the origin of this structure remained in debate [Jackson *et al.*, 1998; Kanbur *et al.*, 2000; Kenkmann, 2003; Kenkmann *et al.*, 2005; Scherler *et al.*, 2006; Okubo and Schultz, 2007].

The models examined here also reveal ways in which a low-impedance surface layer affects the shock wave structure. Because shock deformation is generally a path-dependent process, the duration of the shock wave can affect the type of deformation that material undergoes at the grain-size level [Barnoiun-Jha *et al.*, 2002]. Short pulse duration requires high incident stress values for material failure [Lokhandwalla and Sturtevant, 2000]. As the duration of loading increases, the intensity of plastic deformation as the dominant strain accommodation method should increase [Huffman and Reimold, 1996]. In the cases considered here, a thicker surface layer broadens the shock wave, thereby resulting in lower peak pressures over a longer time period. Similarly, Fig. 5 also reveals that the rise time for the pressure wave decreases, lowering

the strain rate. This evolution of the shock could have ramifications for type and amount of deformation recorded by minerals found in the field. Because of the relatively low peak pressures, shock features probably will not be created, even with large amounts of plastic deformation. Microstructural analysis of samples from the Upheaval Dome, for example, revealed evidence of significant plastic deformation in quartz grains [Kenkmann, 2003], even though diagnostic planar deformation features could not be found until later [Buchner and Kenkmann, 2008]. Some shock amorphization, though, might be expected in these cases, even though the peak pressures are low, because the total duration of loading is greater [Huffman and Reimold, 1996].

In some simulations, two peak-pressure pulses occur (Fig. 3 and Fig. 5). For example, models with a 400-m or 600-m thick layer and an impact angle of 45° show this two-pulse structure, but it is less pronounced for a 30° impact. Tracking the pressure evolution reveals that the first peak is a result of first contact, but the second pressure peak develops as the projectile penetrates through the surface layer and contacts the granite substrate (Fig. 9). Consequently, the distinct nature of the two waves corresponds to continued projectile coupling.

This study focuses on the effects of a low-impedance layer on top of bedrock and the possible signatures after extensive erosion. Extensive erosion of the competent bedrock also can occur. The issue then becomes the identification of the difference between several hundred meters of solid slab erosion versus erosion of the surface layer of a layered target.

Large-scale CTH models with geometries also examined attenuation of peak pressure rates for layered targets compared to impacts directly into bedrock [Stickle and

Schultz, 2011a]. Tracking peak pressure magnitude with depth directly beneath the impact point and 1-km and 2-km downrange of the impact point accentuates the effect of an oblique impact. Peak pressure decays with the form $P \propto r^\lambda$ for a peak pressure (P), the distance (r) below the surface (or, here, the layer-rock interface), and the decay exponent (λ) [e.g., Ahrens and O'Keefe, 1977; Pierazzo and Melosh, 1999]. Directly beneath the impact point, $\lambda \sim -0.3$ to -0.5 for layered targets and $\lambda = -1.1$ for an impact directly into basalt. Downrange from the impact point (1-2 km), and closer to the crater center, the shock attenuation rate ranges from -0.6 to -0.8 for layered targets and -1.1 to -1.2 for impacts directly into basalt.

For models with a layered target, the attenuation rates near the crater center are similar to those seen in Table 3 and Table 4. This illustrates: 1) the directed shock wave; 2) significant deformation even with relatively low overall peak pressures; and 3) the effect of a low-impedance surface on shock-wave attenuation. If pressure with depth can be measured in a given crater, the attenuation rate might then help determine the original impact stratigraphy because a layered target would be expected to have a lower attenuation rate than an impact directly into crystalline bedrock.

Numerical models may not replicate all of the complicated phenomena and interactions due to the assumptions used. For example, Pierazzo [2006] demonstrated that an under-resolved model underestimates peak pressure magnitudes because the shock parameters are averaged over a cell volume. Therefore, smaller cells at a higher resolution will give sharper shock boundaries and higher peak pressures. Here, we use 13 cells per projectile diameter, which (for a 3D CTH simulation) results in an $\sim 10\%$ underestimation of peak pressure versus 20 cells per projectile radius (used as a typical

3D model resolution) [Pierazzo, 2006]. Consequently, the models used here might under-predict peak pressures due to mesh resolution; nevertheless, the conclusions remain essentially unchanged. Even considering a 10% increase, the peak pressures are still very low (5-10 GPa) within non-ejected material.

Laboratory experiments also show that a pumice layer is a more effective shield than the ice layer, even for the same thickness (Fig. 1). This increased shielding may be the result of pore-space collapse, which mitigates peak pressures in the substrate. Because the CTH models considered here do not include porosity, peak pressures will be overestimated, offsetting resolution effects. In a porous sedimentary rock, for example, peak pressures may decay more quickly than in a crystalline rock, and therefore we provide a worst-case scenario. Another possibility is that the impact energy may be transferred into kinetic energy of the ejecta for pumice rather than internal energy and permanent damage for ice or Plasticine. The interaction of these effects and the total combined effect on peak pressure has not yet been quantified.

CONCLUSIONS

Experiments and models both reveal that a low-impedance layer can significantly reduce the peak shock pressures found in the rock record for oblique impacts. A surface layer can act to scatter impact energy or guide the pressure wave along the surface (for very oblique impacts), absorbing up to 60-70% of the impact energy. As a result, only a small percentage of the initial impact energy will be transmitted into the substrate, thereby significantly reducing peak pressures at depth, along with their expression in the rock record. A thick surface layer (3a) can suppress the formation of a crater entirely for

oblique trajectories ($<30^\circ$). When applied to the pre-impact conditions for the Rock Elm crater, 3D CTH models predict that peak shock pressures will fall below the HEL of quartz in non-ejected material, yet still produce permanent deformation. The low peak pressures (on the order of 5-10 GPa) predicted by the model are consistent with field observations of shocked quartz from both Rock Elm [French *et al.*, 2004] and the Upheaval Dome [Buchner and Kenkmann 2008]. Lastly, if pressure with depth can be measured in a given crater, the attenuation rate may help determine the original impact stratigraphy.

Acknowledgements

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TABLES

Table 1. Parameters used in Mie-Grüneisen EOS

Parameter	Pyrex ¹	Plasticine ²	Styrofoam ^{1,3}	PMMA ^{1,3}
Density (g/cc)	2.23	1.69	0.035	1.186
Sound speed (km/s)	2x105	1.4	2.74	2.3
Mie-Grüneisen : S1	1.5	2.978	1.319	1.75
Mie-Grüneisen : S2		-0.694	0	-0.13
Gruneisen Parameter: Γ	1	1	1.18	0.91
Cv (erg/g/eV)	1x10 ¹¹		1.34x10 ¹¹	3.5x10 ¹¹

¹Marsh [1980]; ²Christensen et al [1968]; ³Van Thiel [1977]

Table 2. Mechanical properties used in the CTH models

	Styrofoam	Plasticine^{1,2}	Pyrex	PMMA	Ice³
Yield (MPa)	0.50	0.05	1000	120 ⁴	15
Poisson	0.25	0.44	0.26	0.37	0.3

¹Christensen *et al.* [1968]; ²Austin *et al.* [1980]; ³Gold [1977]; ⁴Misra *et al.* [2009];
Stickle and Schultz 2011b

Table 3. Far-field pressure decay slopes for 45° impact angle

Geometry	Below impact point	1 km DR	2 km DR (crater center)	3 km DR
200 m layer	-1.44	-1.42	-0.97	-0.49
400 m layer	-1.46	-1.49	-1.33	-0.69
600 m layer	-1.27	-1.47	-1.27	-0.82

Table 4. Far-field pressure decay slopes for 30° impact angle

Geometry	Below impact point	1 km DR	2 km DR (crater center)	3 km DR
200 m layer	-1.4	-1.44	-1.14	-0.79
400 m layer	-1.27	-1.57	-1.17	-0.82
600 m layer	-1.17	-1.56	-1.11	-0.79

FIGURE CAPTIONS

Figure 1. Time sequence of damage evolution following 30° impacts into PMMA targets. A) Impact directly into PMMA target, impact angle: 30°, impact velocity: 5.5 km/s, projectile: 0.635-cm Pyrex sphere; B) Impact into a 0.635-cm thick pumice layer over a PMMA target, impact angle: 30°, impact velocity: 5.7 km/s, projectile: 0.635-cm Pyrex sphere; C) Impact into a 0.635-cm thick ice layer over a PMMA target, impact angle: 30°, impact velocity: 5.7 km/s, projectile: 0.635-cm Pyrex sphere. The dashed blue lines represent the top and bottom of the PMMA block, and the projectile size is shown for scale. The red arrow represents the trajectory, the white arrow indicates the “main” damage region and the curved yellow arrow indicates the downrange “tongue” of damage.

Figure 2. Pressure contours at 0.9 sec after impact for three different target geometries. Simulations are of a 200-m dunite sphere impacting at an angle of 45° with velocity of 30 km/s, and target layer thickness of 200 m (a), 400 m (b) and 600 m (c). The quartz HEL is marked at 5 GPa [Stöffler and Langenhorst, 1994], and the transient crater is assumed to have a depth of ~ 1 km. A thinner surface layer results in a larger crater and a sharper pressure wave.

Figure 3. Pressure with time at three depths in the granite substrate below the impact point. (a) 1 km below granite-sediment interface, (b) 2 km below granite-sediment interface, and (c) 3 km below granite-sediment interface. Impact velocity is 30 km/s at 45°, with a 200 m dunite projectile. The three different target geometries are shown in blue (200 m), red (400 m) and green (600 m). Only the 200-m thick sediment layer case experiences peak pressures greater than the HEL of quartz.

Figure 4. Pressure contours at 0.9 sec after impact for three different target geometries. Simulations are of a 200 m dunite sphere impacting at an angle of 30° with velocity of 30 km/s, and target layer thickness of 200 m (a), 400 m (b) and 600 m (c). The quartz HEL is marked at 5 GPa [Stöffler and Langenhorst, 1994], and the transient crater is assumed to have a depth of ~ 1 km. Again, a thinner surface layer results in a larger crater and a sharper pressure wave. The crater is shallower here than in the 45° case.

Figure 5. Pressure with time at three depths in the granite substrate below the impact point. (a) 1 km below granite-sediment interface, (b) 2 km below granite-sediment interface, and (c) 3 km below granite-sediment interface. Impact velocity is 30 km/s at 30°, with a 200 m dunite projectile. The three different target geometries are shown in blue (200 m), red (400 m) and green (600 m). The substrate below the impact point never experiences pressures greater than the HEL of quartz.

Figure 6. Peak pressure decay with distance for two impact angles and three different geometries. Pressure was measured with depth directly below the impact point. The dashed lines show pressure decay for the 30° impact and the solid lines shows pressure decay for the 45° impact. Three different geometries were examined: a 200-m thick sedimentary layer (blue); a 400-m thick sedimentary layer (red); and a 600-m thick

sedimentary layer (green) over crystalline bedrock. The gray box highlights material that will likely be ejected.

Figure 7. Schematic of the final crater size following modification erosion of the sedimentary layer. The assumed crater center is marked by a vertical line and the tracer points for the curves in Fig. 8 are shown in white. The original impact point is shown for reference; impact is from right to left.

Figure 8. Peak pressure decay with distance for two impact angles and three different geometries. Pressure was measured with depth from the sediment-granite interface. The dashed lines show pressure decay for the 30° impact and the solid lines shows pressure decay for the 45° impact. Three different geometries were examined: a 200-m thick sedimentary layer (blue); a 400-m thick sedimentary layer (red); and a 600-m thick sedimentary layer (green) over crystalline bedrock. The gray box highlights material that will likely be ejected. a) 1 km uprange from the assumed crater center; b) depth beneath the assumed crater center; c) 1 km downrange from the assumed crater center.

Figure 9. Time sequence of pressure evolution showing the initiation of the double-pulse structure. Positive pressures are compression, negative pressures indicate extension. The target is a 400-m (2a) thick sedimentary layer on top of crystalline basement. Impact of a 200-m dunite projectile at 30 km/s and an angle of 45° above the horizontal. The top row shows pressure contours perpendicular to the trajectory (i.e., impact into the page). The bottom row shows along-trajectory contours. At 0.2-0.3 sec, the high-pressure compressive waves split, most likely due to the projectile penetrating through the surface layer into the granite resulting in two compressive waves continuing into the substrate. The projectile size is shown for scale, and the black arrows identify the two waves.

FIGURES

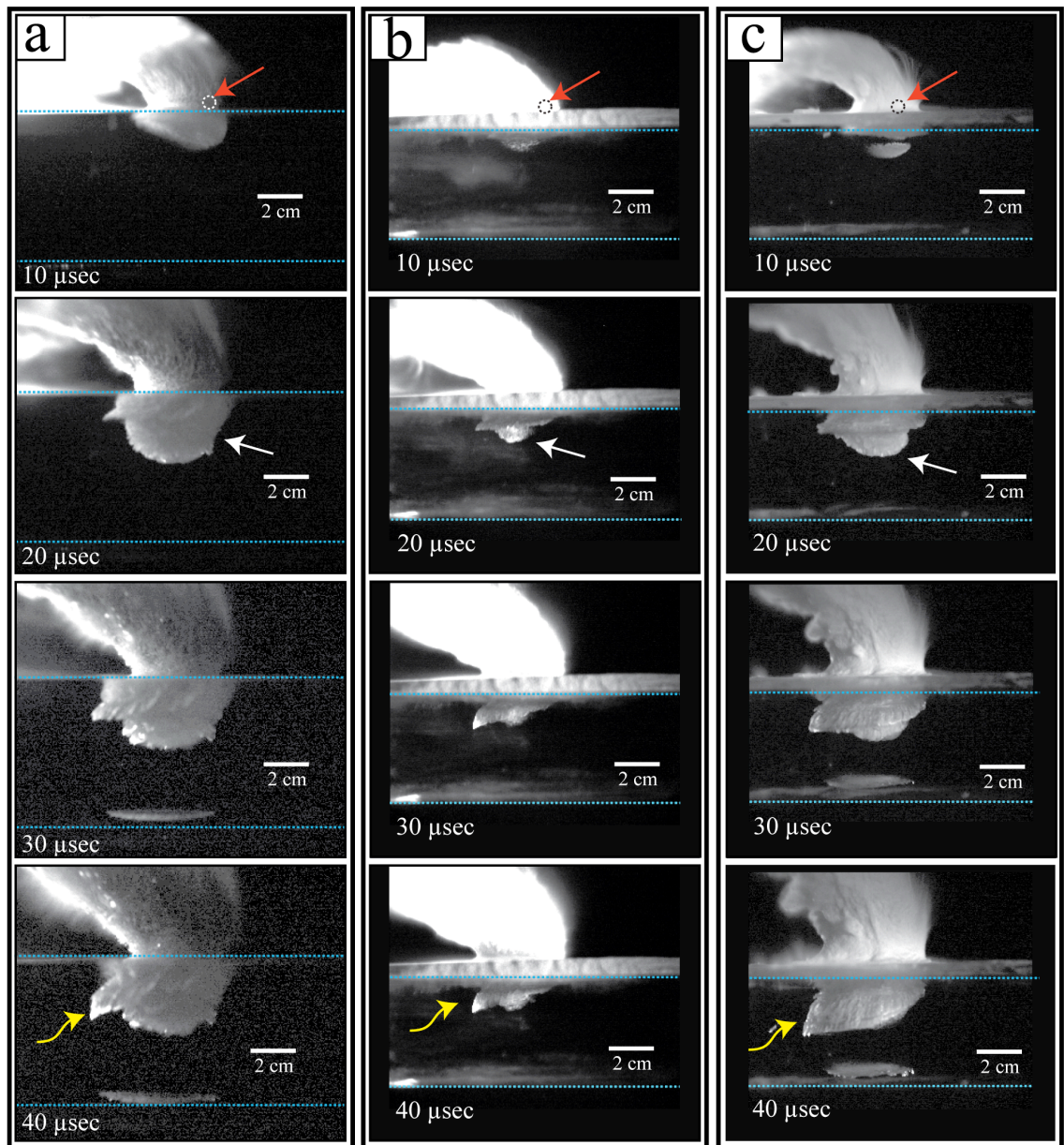


Figure 1

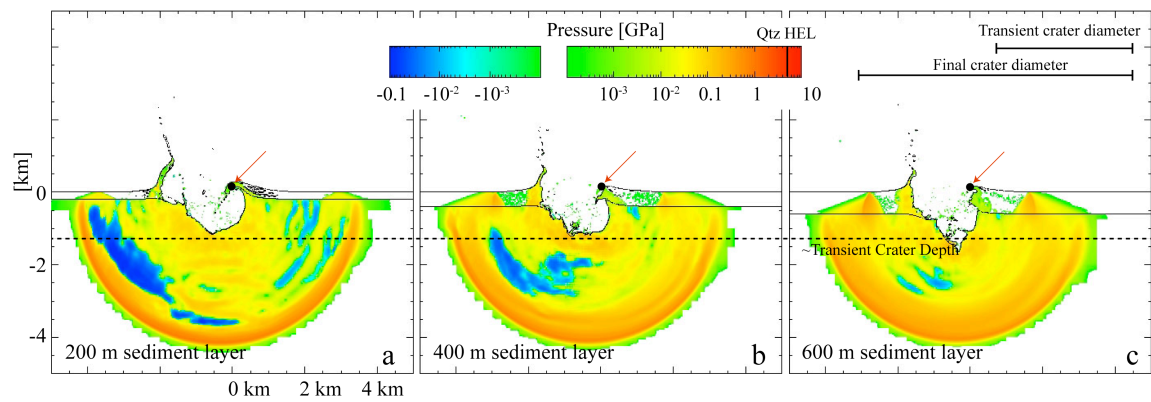


Figure 2

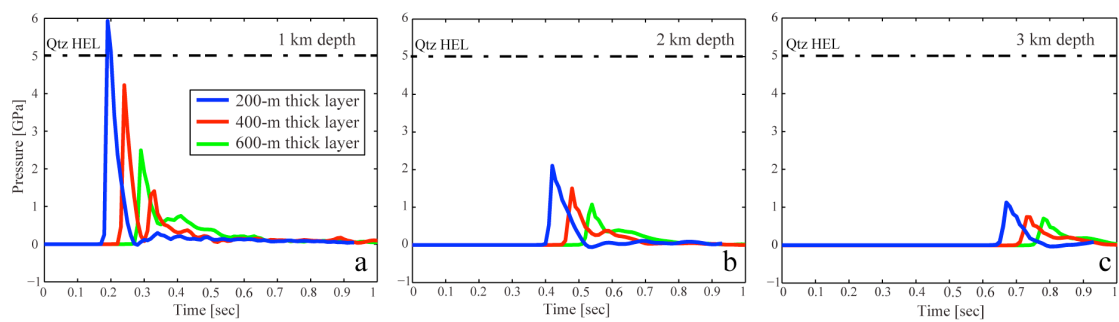


Figure 3

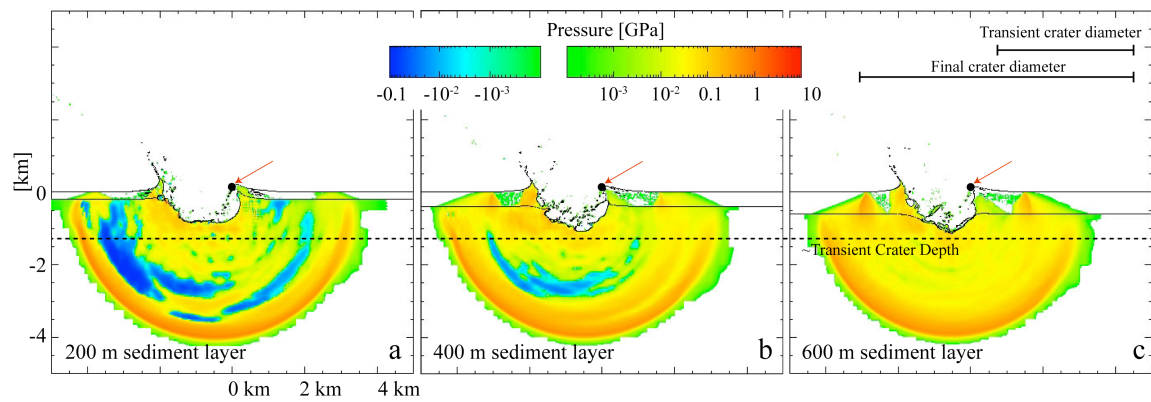


Figure 4

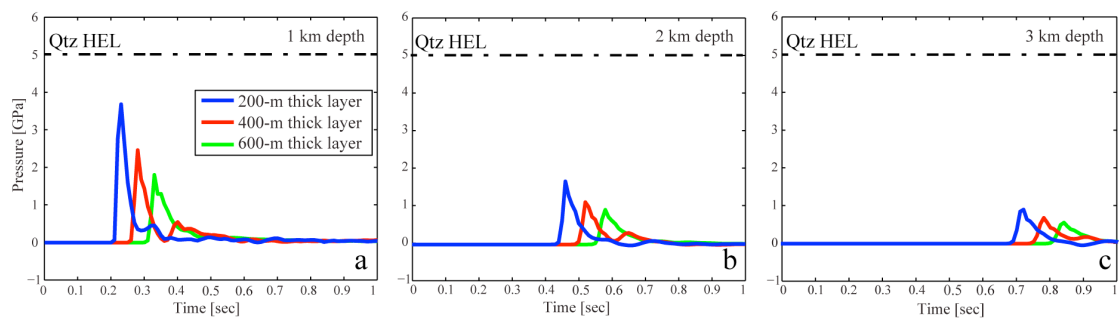


Figure 5

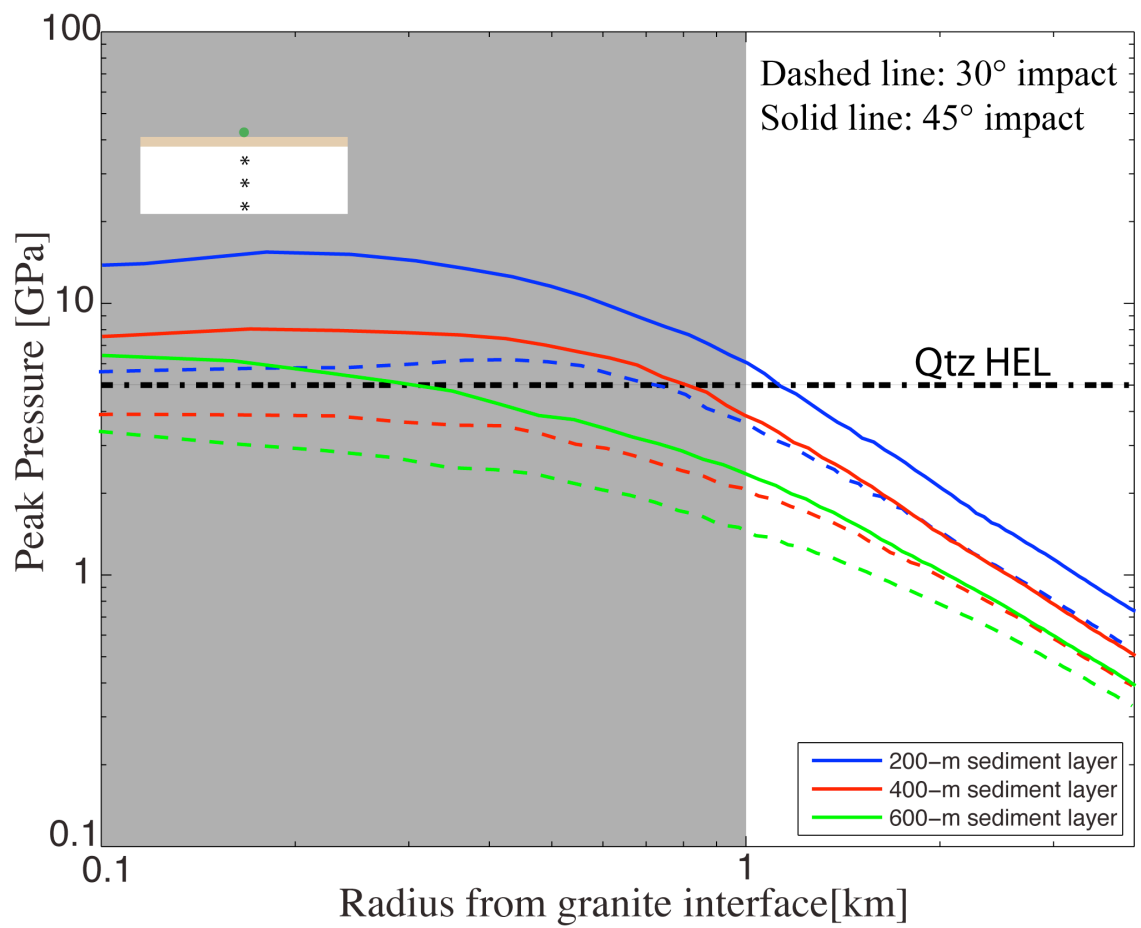


Figure 6

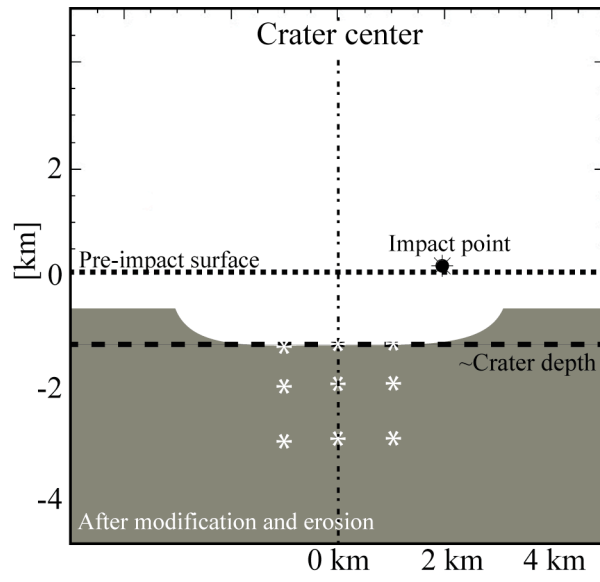


Figure 7

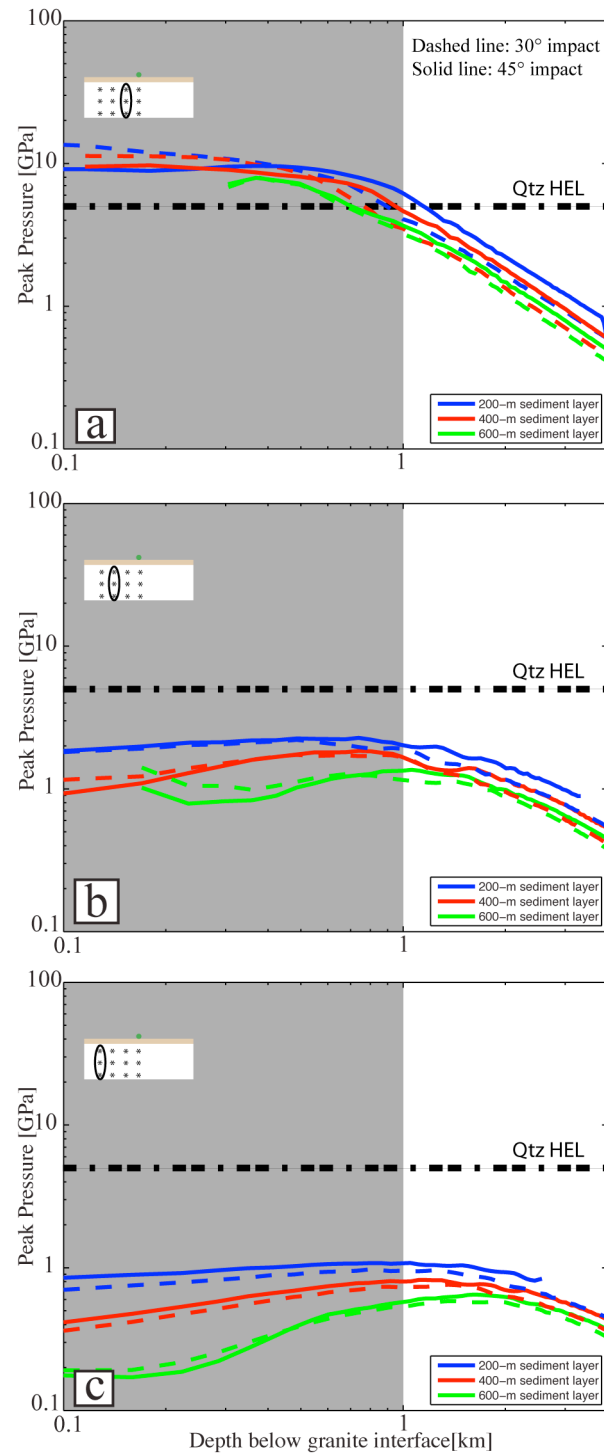


Figure 8

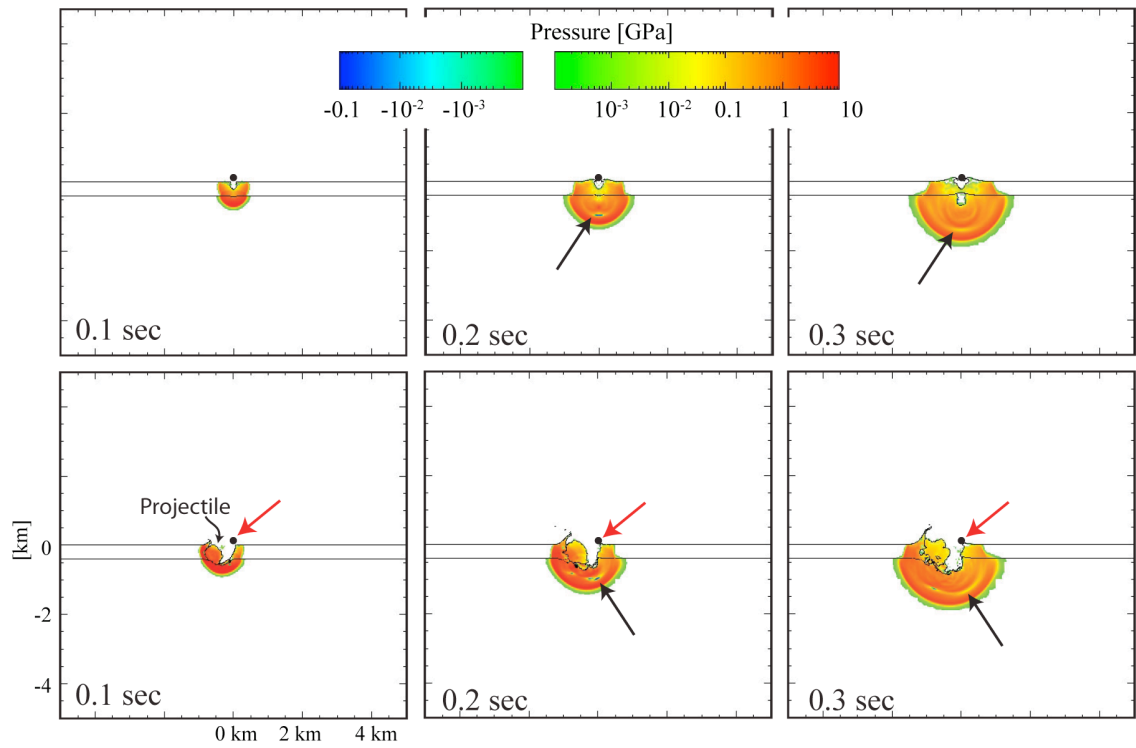


Figure 9

Chapter 5

Subsurface failure in spherical bodies: Implications for asteroid evolution

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Abstract – A new, time-resolved study of damage evolution in spherical targets using a combination of laboratory and companion numerical experiments is presented. This comparison reveals details about subsurface failure within spherical PMMA targets: incipient spallation occurs near the surface at the farside of the target, rarefaction waves coalesce to form a central column of damage centered on the impact point antipode, and deep failure planes result from shear deformation following passage of the shock wave. The orientation of the planar damage features, the number of sub-parallel failure planes, and the location and extent of shallow hazy failure depend on impact angle. Intuition gained from the laboratory and small-scale numerical experiments prompts a new interpretation of surface features observed on asteroids. Large-scale comparisons focus on the grooved terrain observed by the Dawn spacecraft at 4 Vesta. A combination of tensile damage and high values of shear stress indicate that these features may be the result of shear localization in subsurface failure planes similar to what is seen in laboratory experiments. Comparison between the orientation of damage structures in the laboratory and failure regions within Vesta can be used to constrain impact parameters (e.g., the impact point and impact angle).

INTRODUCTION

Comets and asteroids represent survivors of the original planetary building blocks, recording conditions of the early solar system. Nevertheless, nearly all asteroids observed close-up today have impact craters with diameters comparable to the body itself [Bottke *et al.*, 2002]. The size of these craters implies that the interior of these asteroids

must be highly fractured and damaged. Consequently, most small bodies underwent collisional, dynamical and thermal processes over the last 4.5 Ga.

Previous experimental and numerical work examined failure of spherical targets to better understand asteroid evolution, damage structures seen on asteroids, and limits for catastrophic disruption. Impact-induced failure within a spherical target contrasts with failure in a planar target due to curvature of the surface that focuses shock waves towards the center with incipient (if not total) failure at the farside [e.g., Rinehart 1960; Gault and Wedekind, 1969]. This phenomenon is important even for planetary bodies such as the Moon and Mercury [Schultz and Gault, 1975; Hughes *et al.*, 1977; Schultz and Crawford, 2011], and Saturnian satellites [Bruesch and Asphaug, 2004; Moore *et al.*, 2004].

Laboratory impacts into spherical targets have been used to better understand the effects of material properties on collisional outcomes of asteroids [e.g., Fujiwara *et al.*, 1989; Nakamura and Fujiwara, 1991; Martelli *et al.*, 1994; Holsapple *et al.*, 2002]. Impact experiments [Gault, 1973; Gault and Wedekind, 1978; Fujiwara and Tsukamoto, 1980] indicate that impact angle, in conjunction with material properties and impact velocity, significantly affects collisional outcomes. Previous experimental studies show that catastrophic disruption of basalt and glass targets resulted in an intact fragment at the center of the original target (called the “core”) [Gault and Wedekind, 1969; Fujiwara, 1986; Nakamura and Fujiwara, 1991]. This phenomenon is also observed in PMMA targets when they are struck at high velocity.

Laboratory experiments, however, are orders of magnitude smaller than collisions throughout the solar system. Thus, numerical modeling or scaling relationships [e.g., Housen *et al.*, 1983; Holsapple, 1993; Davis *et al.*, 1994] become increasingly important

for understanding collisional histories of asteroids and larger terrestrial bodies. Hydrocode simulations of asteroid disruption were originally benchmarked by comparison with disruption of laboratory-scale spherical targets [e.g., Melosh *et al.*, 1992; Benz and Asphaug, 1994; Asphaug, 1997; Melosh and Ryan, 1997; Ryan and Melosh, 1998; Benz and Asphaug, 1999]. Two-dimensional simulations were generally successful in reproducing fragment size distribution and mean ejecta speeds from laboratory experiments into basalt [Takagi *et al.*, 1984; Hartmann, 1980; Nakamura and Fujiwara, 1991] and weak and strong mortar targets [Davis and Ryan, 1990].

Hydrocode simulations also revealed subsurface damage caused by impacts on asteroids [e.g., Asphaug, 1997; Nolan *et al.*, 2001]. Asphaug *et al.* [1996] used the hydrocode SALE2D [Amsden *et al.*, 1980] to examine subsurface damage on the asteroid Ida, and Asphaug [1997] provided similar analysis for the asteroid 4 Vesta. Their results indicated that stresses from large events into curved, finite target surfaces focus in regions far from the impact point, causing fracture throughout the body. Further, Asphaug *et al.* [1996] showed that the impactor responsible for the Vienna Regio region of Ida may have caused fracturing in Pola Regio. Spacecraft images of Pola Regio reveal sets of parallel to sub-parallel troughs and linear features in this region. The authors concluded that these linear features may be the result of the Vienna Regio impact, and that later impacts may have created stress waves that reactivated these ancient flaws such that the grooves appear fresh on the surface of Ida.

Over the last two decades, missions to asteroids and comets have become increasingly common [e.g., NEAR, Galileo, Deep Impact, Stardust, Hayabusa, EPOXI, Stardust-NExT, Dawn, Rosetta, OSIRIS-REx]. These missions reveal a great deal about

the nature of small bodies in the solar system, including surface properties, morphologies, and shapes. Because internal structure and damage can be manifested on the surface of bodies [e.g., Asphaug *et al.*, 1996; Buczkowski *et al.*, 2008; Schultz and Crawford, 2011], an understanding of subsurface damage caused by impact is important for fully understanding data returned by these missions.

The present study first describes a new time-resolved experimental approach for assessing damage in spherical targets. This description is followed by a detailed comparison between subsurface damage in laboratory experiments and small-scale CTH simulations. We then discuss the results of CTH simulations on the scale of a particular asteroid: 4 Vesta. We finish with discussion of the damage structures in spherical targets, including formation mechanisms, differences with planar targets, and implications for asteroid evolution and future study.

METHODS AND APPROACH

Previous studies focused on planar polymethylmethacrylate (PMMA) targets in order to track the evolution of subsurface damage following oblique impacts for both impacts directly into PMMA [Stickle and Schultz, 2011] and impacts into layered PMMA and geologic targets [Chapters 3 and 4]. At planetary scales, however, target curvature creates shock-wave interactions that significantly changes the damage pattern (and process). Here, impacts into transparent PMMA spheres are directly compared with three-dimensional CTH models. These results then provide insights into extrapolations to large-scale planetary models.

Laboratory Experiments

A suite of laboratory experiments was performed at the Ames Vertical Gun Range (AVGR) at the NASA Ames Research Center in Mountain View, California. The AVGR is a two-stage light gas gun that achieves impact velocities from $\sim 0.5 - 7$ km/s (depending on projectile size). The barrel can rotate from $0 - 90^\circ$, in 15° increments, allowing the target to stay oriented correctly with respect to gravity, which is especially important when studying impacts into granular or fluid targets. The targets are set up inside a 2.5-m diameter vacuum chamber, so a wide variety of shapes and sizes can be accommodated. The vacuum chamber can be maintained at a vacuum level below 0.3 torr, or filled with different gasses to simulate various environments. High-speed cameras (up to 1 million frames per second) are used to record the impact events.

For this study, transparent PMMA spheres were used as the target. PMMA is a transparent acrylic that becomes opaque under high strain and allows tracking the evolution of impact-induced damage. At room temperature and high-strain rates, PMMA is brittle and has mechanical properties similar to that of the upper crust of the Earth, which makes it an ideal rock analog in high-rate laboratory experiments [de Joussineau *et al.*, 2003; Rosakis *et al.*, 1999, 2004, 2008; Rittel and Brill, 2008; Nasraoui *et al.*, 2012]. PMMA, along with some other transparent polymeric materials, also exhibits birefringence, making it useful for studies of dynamic failure processes because stress fields can be mapped using photoelasticity techniques [e.g., de Joussineau *et al.*, 2003; Rosakis *et al.*, 1999; Rosakis, 2002; Misra *et al.*, 2009].

For this study, spherical targets with a 10-cm diameter were placed on top of a thin (0.3 cm) plastic cylinder protruding from a sand surface. Pyrex spheres (0.635-cm in

diameter) impacted the target at ~ 5.5 km/s with impact angles ranging from 40° - 65° . The downward direction of impact minimized interactions with the thin cylinder supporting the sphere (evident in imaging and in lack of surface damage to the sphere). The evolution of the damage was tracked using two high-speed cameras (Shimadzu, HV-1) using frame rates of 250,000 to 500,000 frames per second over the first 200 μ sec after impact, sufficient time for the damage zones to finish growing. The frame rate of 500,000 frames per second also provided adequate time resolution to track the damage zone growth rate.

CTH Models

CTH is a multi-dimensional, multi-material, two-step Eulerian hydrocode model developed by Sandia National Laboratories in Albuquerque, New Mexico [McGlaun *et al.*, 1990]. This code is used widely to model hypervelocity impacts into planetary surfaces because it is designed to model strong shock processes. The code also encompasses a variety of material models and equations of state (EOS).

All calculations for this study were performed in a three-dimensional rectangular coordinate system, which is necessary to model oblique impacts. The CTH models here are used to identify conditions of failure observed within the impacted spheres for identical impact parameters. Adaptive Mesh Refinement (AMR) [McGlaun *et al.*, 1990; Crawford, 1999] is used to refine the mesh around high-pressure regions (i.e., the shock wave), while leaving other portions of the target at a lower resolution, which significantly reduces computational time. The maximum resolution for the laboratory-scale models is 0.026 cm (~ 16 cells per projectile radius (cppr)).

Sophisticated constitutive models are necessary for accurate models of material behavior undergoing differential stress. In these models, the Pyrex projectile is assumed to behave as a geologic material with a pressure-dependent yield surface. In order to track subsurface failure in PMMA, however, a slightly more complicated failure model is necessary. A Von Mises plasticity model is used to track the deformation, which is coupled with the Johnson-Cook Fracture (JCF) model. This model reveals regions of plastic failure (which are taken to be regions of shear deformation) within the PMMA sphere. The JCF model is a scalar damage model used to predict failure of materials [Johnson and Cook, 1985]. A damage parameter, D , ranges from 0 (pristine, undamaged material) to 1 (failed material), where D is a function of equivalent plastic strain rate, local value of plastic strain to fracture, pressure, local yield stress, temperature and loading path. In order to better understand the failure modes and to minimize the parameter space, D is assumed to be a function of the local value of plastic strain to fracture only. Shear failure (defined at $D=1$) will occur when the material stresses exceed the yield stress and then the material undergoes a user-specified value of plastic strain. Here, we assume that the material has a yield stress of 120 MPa and that failure occurs at 10% strain, after a previous study by Stickle and Schultz [2011].

The JCF model only tracks failure due to shear deformation. Nevertheless, this model is often used in conjunction with a separate spallation-failure criterion in order to predict failure of pre-damaged material or material experiencing excess hydrostatic tension. For this study, however, shear and tensile failure are considered separately. Damage by extensional failure (spallation) occurs when the material undergoes stresses higher than the maximum tensile stress. In reality, later occurring shear can capitalize on

zones under extension; hence, it would be useful to have an integrated model. Our approach, however, is to isolate and identify these two modes.

An equation of state relating pressure and volume is necessary in order to close the equation set. Here, a Mie-Grüneisen EOS is used for both Pyrex [Marsh, 1980] and PMMA (available within the CTH package). The Mie-Grüneisen EOS provides a good representation of PMMA below 25 GPa, but can be used with confidence up to pressures of 100 GPa. Because we are not examining the impact point, but rather areas far away that are at lower pressures, this EOS is a valid representation for our model. Table 1 summarizes the model parameters used in the CTH simulations.

Laboratory-scale experiments provide important insights into processes occurring following oblique impacts and direct comparisons with numerical models establish confidence for larger scale applications. The next step considered a 5 km/s (the mean asteroidal impact velocity) impact into the differentiated asteroid 4 Vesta. This asteroid was modeled as a differentiated body with a diameter of 578 km, and core size and thickness were assumed to follow the model of Ruzicka *et al.* [1997]. The diameter of the sphere was taken to be the longest axis of Vesta [Thomas *et al.*, 1997; Ruzicka *et al.*, 1997]. The metallic core has a diameter of 164 km, and was modeled using the ANEOS equation of state (i.e., Analytic Equations of State) [Thompson and Lauson, 1984; Thompson, 1990] for iron and a Von Mises yield surface. The dunite mantle and basaltic crust have thicknesses of 165 km and 42 km, respectively. The calculations used ANEOS for dunite, and a Sesame table for basalt. The selection of dunite and basalt provide a reasonable match for the composition of 4 Vesta [McCord *et al.*, 1970; Binzel *et al.*, 1997; Thomas *et al.*, 1997]. The impactor was assumed to be an undifferentiated

dunite sphere with a radius of 50 km. Dunite and basalt are modeled as geologic materials with a pressure-dependent yield surface.

Davis *et al.* [1985] show that gravitational self-compression of material is important in understanding cratering processes on asteroids. Thus, the calculation also included self-gravity for the asteroid and the impactor based on a parallel implementation of the Barnes and Hut [1986] algorithm, as well as AMR. The asteroid was initialized at a constant temperature of 297 K, with surface gravity $\sim 0.26 \text{ m/s}^2$ [Ruzicka *et al.* 1997]. Initial density, pressure and gravity profiles through the body are shown in Figure 1. The maximum resolution for the large-scale simulations was 2.5 km (20 cells across the projectile), which was adequate to capture shock compression, release and failure within the body.

DAMAGE IN A SPHERICAL TARGET

The laboratory experiments provide a clear view of damage growth as well as insight about particular damage structures, but it is sometimes difficult to understand all of the processes that are occurring. Numerical models, however, track the state of the material following impact and the modes of deformation and damage growth and fill this gap in understanding. Conversely, materials deform in complicated ways, and material properties are not always well constrained. Instead, experiments provide an important reality check for the complicated numerical models and a way to benchmark our simulations. This section will first detail the results of laboratory experiments into spherical targets before detailing results of CTH models for comparison. The last portion of this section examines results of asteroid-scale impact simulations.

Laboratory Experiment Results

A suite of impact experiments was performed at the NASA Ames Vertical Gun Range examining the effect of impact angle on the initiation and growth of subsurface failure planes. Impact velocities were kept approximately constant (5.5 km/s) and impact angle was varied between 40°-65°.

A time sequence of typical failure evolution is shown in Figure 2. Directly following impact, damage begins to grow asymmetrically beneath the impact point, concentrated downrange. Approximately 24 μ sec after impact, a shallow subsurface haze forms downrange (about 90°) from the impact and is composed of small failure discs just below the surface. The haze grows around the sphere, towards the impact point antipode. Around 40 μ sec after impact, a stalk of damage grows into the sphere from the farside of the target. This stalk grows up towards the center of the sphere, with the tip emerging around 60 μ sec as it grows above the haze boundary. Following this growth, planes of failure aligned perpendicular to the central column begin to grow. These planes are seen clearly in Figure 2 at 88 μ sec and continue to grow outward until about 100 μ sec after impact. Following damage formation, the finished structure resembles a blooming flower, and is termed a “tiered rosette” throughout the rest of the paper (this structure is also observed in Schultz and Crawford [2011], where the authors call it a “tree-like” feature). Figure 3 provides a closer view of this structure (same experiment in Figure 2). Planes perpendicular to the central damage column, which points up towards the center of the sphere, comprise the “petals” of the tiered rosette structure. The orientation of these final damage structures depends somewhat on impact angle and velocity (Figure 4), but they all evolve in the same manner. Beneath the impact point, a large failure region

grows. This region is centered on a point downrange from the impact point, common to most oblique impacts. Late in the damage growth process (following the completion of the subsurface damage growth), large pieces of the target spall from the impact-side of the target due to the small size of the target.

Laboratory-Scale CTH Results

Impact conditions for the CTH simulations were identical to the experiments. The model corresponding to the experiment shown in Figure 2 was replicated for the shear failure (Figure 5) and the spall failure (Figure 6) criteria. The JCF damage parameter is used to illustrate regions of the target failing in shear (Figure 5). $D=1$ indicates material that is completely failed (corresponding to opaque regions in the laboratory experiments), whereas values of $0 < D < 1$ indicate damaged and weakened material. These figures show 2-dimensional slices through the 3-dimensional model at the center planes of the sphere along the trajectory (left column) and parallel to the trajectory (right column).

Figures 5 and 6 illustrate the evolution of the damage zones, but it is also necessary to examine final damage structures using both failure criteria. Final damage patterns (time = 108 μ sec after impact) are shown for this experiment in Figure 7 for the same two views shown in Figures 5 and 6. The near-surface failure seen in the spall criterion (right hand side of A and B) wraps around the sphere in the 3D target and is shown as a thin region here.

Damage due to spallation overlain onto damage from shear damage allows a comparison to the damage structures seen in the experiments (Figure 8). The 2D CTH

slice reveals the subsurface failure extent more clearly than in the experiments where the haze near the surface obscures some of the deep subsurface failure.

Laboratory experiments reveal that varying the impact angle affects the orientation of the damage structures. Consequently, comparison models were run with identical impact conditions for each of the AVGR experiments. The resulting evolution of the damage (Figure 9) remains similar to the 45° reference set (Figures 5 and 6).

One of the advantages of numerical models is the ability to isolate different processes in detail. Tracking pressure throughout the impact event (Figure 10B, 10E) illustrates the shock wave traveling through the sphere as it interacts with the curved surface and reveals areas of the target are undergoing tensile or compressive stresses. These values can then be compared with other parameters, such as the magnitude of the shear stress (here, shown by a form of the second invariant of the deviatoric stress tensor, $J2P$; Figure 10A, 10D) or damage evolution (D , Figure 10C, 10F) in order to better understand failure processes and mechanisms within the target. The black and white dotted outlines in 10A and 10C show the outline of compressive (black) and extensional (white) regions overlain on top of the shear stress magnitude. Here, the target has been rotated and the impact point is now at the top of the sphere.

Large-Scale CTH Results

CTH models simulating an impact into asteroid 4 Vesta reveal details about possible stress states causing internal damage at much larger scales. During the first 60 sec after impact (the time for the shock wave to cross the body once; corresponding to ~30 μ sec in laboratory experiments), the subsurface experiences extensive shear stress (Figure 11).

In the next several hundred seconds, the stress state becomes more complicated, and large regions of the subsurface undergo extreme tensile stresses in addition to shear stress (Figure 12). The regions of maximum tensile stress are located downrange and opposite of the impact point, resulting in an asymmetric damage pattern within the body, similar to what is seen in laboratory experiments. Material on either side of the crater will likely delaminate and leave behind exposed mantle material, and a large portion of the asteroid downrange of the impact point will be fractured. Lastly, Figure 12 reveals a large region near the core mantle boundary will fail and fracture. While different in detail from the small laboratory experiments, the inferred sequence and style of failure is intriguingly similar.

DISCUSSION

Laboratory Scale Processes

Laboratory experiments of oblique impacts reveal that deep, antipodal damage is not centered on the antipode to the crater center, but rather the point of first contact (Figure 4). The antipodal damage is separated into two main regions: the center column of damage pointing back towards the impact point, and the planes perpendicular to the central damage column (Figures 2, 7, 8). These two main regions result from different processes. The central column of damage is due to tensile failure as shock waves coalesce and concentrate at the farside of the target [Rinehart, 1960] (Figure 6, 7, and 10). The planes, however, are formed by shear stresses set up behind the shock wave (Figures 5-8, and 10), similar to the blades observed in oblique impacts into PMMA blocks [Stickle and Schultz, 2010; Chapter 2]. Regardless of impact angle, the interior

failure planes begin to form around 50 μ sec after impact (Figure 2, 5), when shear stresses are highest near the middle of the sphere (Figure 10). Further, the region of failure is under compression, inhibiting tensile fracturing.

Impact angle also affects the orientation of the rosette feature (Figure 4, 9). In general, the central column is offset from the crater center antipode and the orientation angle steepens for increasingly oblique impacts (Figure 4). Similarly, the angle between the extending planes and the normal to the line connecting the impact point to its antipode also depends on impact angle (Figure 13 and Table 2). The orientation of the failure planes becomes less orthogonal to the normal connecting the impact point and its antipode as impact angle decreases.

The near-surface, hazy region enveloping the downrange portion of the sphere represents incipient spallation. Laboratory experiments examining catastrophic disruption resulted in entire layers of basaltic and glass spheres spalling from small, spherical targets [e.g., Gault and Wedekind, 1969; Nakamura and Fujiwara, 1991; Nakamura *et al.*, 1994]. The three experiments in this study did not experience that level of disruption, however cracks are present at the antipode to the impact point, suggesting that material may have spalled from the farside of the target for slightly higher impact energy. The haze may therefore represent the beginning stages of large-scale spallation and disruption of the target. Conversely, glass spheres did not develop the interior tiered rosette pattern, due to relief in strain caused by spallation or the nature of amorphous glass [Schultz and Gault, 1975].

Vesta from Dawn

The Dawn mission is currently orbiting the giant asteroid 4 Vesta. The goals of the mission are to characterize the conditions and processes of the earliest epoch in the solar system by studying two of the largest asteroids (protoplanets) remaining in the asteroid belt [Russell *et al.*, 2007]. Earth and Hubble Space Telescope-based observations provided first-order views of Vesta, both indicating that Vesta has a basaltic crust indicative of melting and extensive thermal evolution, and is a dry, differentiated body [McCord *et al.*, 1970]. Further, the reflectance spectrum matches the composition of the HED meteorites [e.g., McFadden *et al.*, 1977; Feierberg and Drake, 1980; Feierberg *et al.*, 1980; Gaffey, 1997], and dynamical models indicate that the HED meteorites (and the Vesta dynamical family) likely originated from Vesta [Williams 1989; Zappalá *et al.*, 1995; Binzel and Xu, 1993; Burbine *et al.*, 2001]. The asteroid is an oblate spheroid, with radii of 289-km, 280-km and 229-km ± 5 km, and it has two large craters on the south pole [Thomas *et al.*, 1997]. The mass of Vesta is $2.71 \pm 0.1 \times 10^{20}$ kg [Michalak, 2000], with a bulk density of 3750 ± 400 kg/m³, and a core size up to 25% by mass [Dreibus *et al.*, 1997; Ruzicka *et al.*, 1997; Righter and Drake, 1997].

Images returned from the Dawn spacecraft show two sets of troughs on Vesta's surface (Figure 14): one set parallels the equator, and the other is seen near the north pole [Le Corre *et al.*, 2012; Schenk *et al.*, 2012; Scully *et al.*, 2012]. The equatorial trough set contains ~85 linear structures with lengths varying from 19-380 km and widths up to 15 km. The longitudes of the poles to these structures vary, but seem to circle the central mound of the large south-pole impact basin Rheasilvia [Buczkowski *et al.*, 2011]. Nearer to the north pole, the primary structure is 390 km long and 38 km wide. There are

currently 7 mapped linear structures in this set, with lengths from 31-212 km, and the poles to these structures cluster near the center of the second, smaller impact basin near the south pole [Buczkowski *et al.*, 2011]. The two sets of troughs crosscut each other near the equator at approximately 300-330° W longitude (Figure 15), and they meet at an angle of 30°. Based on the crosscutting relationships, the equatorial troughs are younger than those near the north pole. Further, the equatorial troughs also seem to be more well-preserved than the majority of Vesta's surface, indicating that they formed after the north polar troughs [Buczkowski *et al.*, 2011]. Alternatively, the troughs may be older sets of faults that have been re-activated since their formation (following [Asphaug, 1996]), making a precise age relationship difficult to determine.

Large-scale CTH models in conjunction with the insights gained from laboratory experiments provides new clues into the formation of the trough sets on Vesta. The upper limit for dynamic strength of basalt is 180 MPa [Cohn and Ahrens, 1981], whereas the lithostatic pressure at the core-mantle boundary is 130 MPa (Figure 1). Material is considered fractured when stresses exceed the lithostatic load (the overpressure) by 180 MPa, which gives a maximum strength (for any depth within Vesta) of ~310 MPa corresponding to the transition from cyan to light green in the maximum tensile stress diagrams (Figures 11 and 12). Consequently, a large region of the asteroid should have been subjected to tensile stresses great enough for fracture and failure (Figures 11 and 12). Just as in the laboratory experiments, shear processes are likely important in subsurface evolution (Figure 12). The white outlines in Figure 12B and 12D indicate the regions where tensile stresses are large enough to cause fracturing. These regions overlap with, or form directly before, regions of high shear stress. Temporally, the combination

of these two stress states suggests that the subsurface of Vesta may be damaged or fractured due to tensile stresses, but then fail and slide due to high shear stresses behind the shock wave. This pattern is seen even to late times (Figure 13), as the shock and rarefaction wave reflect and coalesce throughout the body.

The location of subsurface failure regions within Vesta suggests a possible formation scenario for the troughs seen on the surface. It is known that seismic stresses can be enhanced at the antipode to large impacts, which can result in increased damage formation [e.g., Schultz and Gault, 1975; Asphaug *et al.*, 1996; Schultz and Crawford, 2011; Meschede *et al.*, 2011]. Numerical studies by Asphaug *et al.* [1996] and Benz and Asphaug [1994] reveal that the grooves (troughs) in Pola Regio, a region of the asteroid Ida, and the grooves on Phobos may have formed by large impacts [Fujiwara and Asada, 1983; Asphaug and Melosh, 1993]. Smoothed-particle Hydrodynamics (SPH) simulations show that far-field stress waves will focus and cause local damage in the subsurface of Ida, which may then be reactivated by later impacts [Asphaug *et al.*, 1996]. The CTH calculations shown here reveal that similar processes may have occurred on Vesta.

In contrast with previous studies on asteroid damage, the large-scale simulations here suggest that the deep failure within the body may be due to mixed-mode processes and not purely a result of tensile stresses. The combination of high shear stress magnitudes overprinting weakened or pre-damaged material lasts for hundreds of seconds (Figure 12). A typical earth quake rupture on Earth propagates at approximately 3 km/s [Stein and Wyssession, 2003]. Assuming: 1) a similar propagation rate for Vesta, and 2) continued stress loading will cause the deep fractures to grow to the surface, fractures

forming deep within the body will reach the surface after approximate 100-150 seconds. During this time period, damaged material is continually subjected to high shear stresses, which creates localized shear planes.

Observations of impacts on Vesta combined with laboratory experiments also provide insight in other critical impact parameters. The south pole of Vesta is covered by a large impact basin (provisionally called Rheasilvia) with a diameter approaching that of Vesta (Figure 16). Rheasilvia has an elevation range of ~ 40 km, and contains a central mound. If the subsurface shear planes observed in the laboratory are small-scale analogs for the trough features observed on Vesta, then the orientation of the damage region might indicate the impact location and angle by the angle of offset from the impact crater center antipode. Table 2 shows that the angle between the two antipodes decreases from $\sim 13^\circ$ to 5° as impact angle increases from 40° - 65° . This variation is consistent with results from simulations of the South-Pole-Aitken Basin formation on the lunar surface [Schultz and Crawford, 2011]. Consequently, the Rheasilvia impactor collided at an angle less than 40° with respect to the surface tangent (Figure 17). Impact angles higher than 40° result in improbable impact points too near the crater center (Figure 17B and 17D). Further study will be done to fully characterize the variation with impact angle such that more stringent constraints can be placed on the impact location and trajectory.

CONCLUSIONS

Laboratory experiments coupled with three-dimensional CTH models reveal details about subsurface failure within spherical targets. Laboratory experiments are characterized by three main damage regions: the intensely fractured and spalled region

surrounding the impact point; central and antipodal failure plains (the “rosette”); and shallow, near-surface incipient spallation and shear downrange from the impact point. Rarefaction waves reflected off the free surface converge inside the sphere centered on the antipode to the first contact (offset from the crater center) and create a damage column. Numerical simulations reveal that deep failure planes result from shear deformation following passage of the shock wave. The orientation of the planar damage feature, the number of sub-parallel failure planes, and the location and extent of shallow hazy failure depend on impact angle.

Insight gained from the laboratory and small-scale numerical experiments prompts a new interpretation of surface features observed on asteroids. Sets of linear troughs observed on the asteroid 4 Vesta represent just one example, but these interpretations could apply to similar features occurring on other small bodies. Three-dimensional CTH calculations of large, oblique impacts onto a differentiated Vesta induce damage over large regions of the subsurface. Such simulations confirm that the linear features may be surface expressions of subsurface failure and faulting. A combination of tensile damage and high values of shear stress indicate that these features may be the result of shear localization in subsurface failure planes similar to what is seen in laboratory experiments. Comparison between the orientation of damage structures in the laboratory and failure regions within Vesta can be used to constrain impact parameters: the Rheasilvia basin was likely formed by an impactor colliding with Vesta at ~ 5 km/s and an angle less than 40° . Future detailed structural studies of the surface troughs on Vesta provide a means to test these hypotheses.

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TABLES

Table 1. EOS and strength model parameters used in the CTH calculations

Parameter	Pyrex¹	PMMA²	Basalt	Dunite	Iron
Density (g/cc)	2.23	1.186	2.86	3.32	7.85
Sound speed (km/s)	2	2.3	5.17	6.59	4.99
Linear coefficient of the Us-up Hugoniot curve: S1	1.5	1.75	--	--	--
Quadratic coefficient of the Us-up Hugoniot curve: S2	0	-0.13	--	--	--
Gruneisen Parameter: Γ	1	0.91	--	--	--
Cv (erg/g/eV)	1×10^{11}	3.5×10^{11}	--	1.35×10^{11}	5.16×10^{10}
Yield Strength (MPa)	1000	120	1000	1000	1000
Yield Strength at P=0 (MPa)	2	--	2	2	
Poisson's ratio	0.26	0.37	0.26	0.26	0.28
Strain to Failure	--	10%	--	--	--
Slope of the yield surface at P=0: dy/dp	0.5	--	0.5	0.5	--
Melting Temperature, Tm (eV)	0.25	0.25	0.25	0.25	0.16

¹Marsh [1980]

²EOS parameters are library coefficients; strength parameters are based on a parameter study in Stickle and Schultz [2011]

Table 2. Orientation of damage structures measured for three different laboratory experiments

Impact angle [deg]	Number of "petals"	Angle to normal (α) [deg]	Angle between impact point and crater center antipodes [deg]
40	3	$\alpha_1 = 19$ $\alpha_2 = 12$ $\alpha_3 = 7.6$	13
47	3	$\alpha_1 = 15-16$ $\alpha_2 = 14-15$ $\alpha_3 = 12$	13
65	1	$\alpha_1 = 13$	5

FIGURE CAPTIONS

Figure 1. Pressure, density and gravity as a function of radius at time = 0 for simulated asteroid 4 Vesta. Vertical dashed lines indicate transitions between crust, mantle and core. The asteroid was modeled as a 578-km diameter differentiated body with a 164-km iron core, 165-km thick dunite mantle and 42-km thick basaltic crust [after Ruzicka *et al.*, 1997].

Figure 2. Time sequence showing the damage evolution within a spherical target. The projectile was a 0.635-cm Pyrex sphere into a 10-cm PMMA sphere at an angle of 47 degrees and a velocity of 5.6 km/s.

Figure 3. Close view of the “rosette” structure (planes extending from a central failure column) for the experiment shown in Figure 2. The “petals” form incomplete planes around the central damage column at various depths.

Figure 4. Comparison of final damage structures for three different impact angles. The red line shows the trajectory of the projectile, the light blue line shows the antipode to the crater center, and the green line indicates the antipode to the impact point. The approximate crater size, measured from high-speed images of the impact, is shown by the white hash marks. Top: impact of a 0.635-cm Pyrex sphere into a 10-cm PMMA sphere at 5.4 km/s at an impact angle of 40 degrees to the surface tangent plane. Middle: impact of a 0.635-cm Pyrex sphere into a 10-cm PMMA sphere at 5.6 km/s at an impact angle of 47 degrees; (bottom) impact of a 0.635-cm Pyrex sphere into a 10-cm PMMA sphere at 5.4 km/s at 65 degrees. The insets show close-up views of the rosette structure. For increasingly oblique impact angles, the damage planes are elongate in the downrange direction (also shown in Figure 2). The impact antipode is also marked in the inset for reference, along with the impact point indicating impact angle and location. Note that the central damage column is centered around the impact point antipode, not the crater center, for oblique impacts.

Figure 5. CTH model matched 1:1 for the impact shown in Figure 2 showing damage due to shear deformation. Impact conditions: 0.635-cm Pyrex sphere impacting at an angle of 47° and 5.6 km/s. Times correspond to panels in Figure 1. D=0 is undamaged material and D=1 indicated failed material. Left: 2-dimensional slice through the center plane of the sphere parallel to the trajectory. Right: 2D slice perpendicular to the trajectory. Original sphere diameter and projectile size are shown for scale. The arrow indicates impact trajectory.

Figure 6. CTH model matched 1:1 for the impact shown in Figure 2 showing damage due to tensile failure (spallation). Impact conditions: 0.635-cm Pyrex sphere impacting at an angle of 47° and 5.6 km/s. Times correspond to panels in Figure 2. D=0 is undamaged material, while D=1 is failed material. Left: 2-dimensional slice through the center plane of the sphere parallel to the trajectory. Right: 2D slice perpendicular to the trajectory. The original sphere diameter and projectile size are shown for scale. The red arrow indicates the impact trajectory.

Figure 7. Damage structures 108 μ sec after impact. Conditions are the same as the experiment in Figure 1. A) Shear failure criterion (left) and spall failure criterion (right) from the side (parallel to the trajectory). B) Shear failure criterion (left) and spall failure criterion (right) along the trajectory. Note the central columnar damage zone in the spall criterion, whereas the damage planes align roughly perpendicular to the stalk in the shear failure criterion. The projectile size and original sphere cross-section are shown for scale. The red arrow indicates the impact trajectory.

Figure 8. Damage structures 108 μ sec after impact. A) “Combined” failure criteria: spallation is overlain on shear failure; B) Corresponding experiment. Projectile size is shown for scale, and the red arrow indicates impact trajectory.

Figure 9. CTH models comparing to AVGR experiments of a 0.635-cm Pyrex sphere into 10-cm PMMA sphere. The damage parameter is shown for two cross-sections: parallel to the trajectory (left) and perpendicular to the trajectory (right) at ~ 100 μ sec after impact. Projectile and original sphere size shown for scale. A) Impact angle: 40° , Impact velocity: 5.4 km/s. B) Impact angle: 47° , Impact velocity: 5.6 km/s; C) Impact angle: 65° , Impact velocity: 5.2 km/s.

Figure 10. Shear stress and pressure through time following the impact of a 0.635-cm Pyrex projectile into a 10-cm PMMA sphere at 40° and 5.4 km/s. Horizontal rows are all at the same time after impact, which is noted in the left-hand column. Images are 2D slices through the 3D model, and the planes go through the center plane of the sphere (location indicated by black dotted lines in A and D). Frames A, B, and C are perpendicular to the trajectory, whereas D, E, and F are parallel to the trajectory; projectile size is shown for scale. The material apparently suspended within the crater in frames A-C is actually part of the ejecta that has folded over, which can be seen in D-F. Frames A and D show the magnitude of the shear stress (J2P). Frames B and E show pressure through time. Frames C and F show the damage parameter, D . Black and white curves outline regions in tension (white) and compression (black) from B and E: positive values indicate compression, and negative values indicate tension. White curves in C and F outline regions with the highest values of J2P, which indicates that damage forms and grows in regions of high shear stress.

Figure 11. Shear stress and pressure for the first 100 sec after impact of a 50-km dunite projectile into the asteroid Vesta. The 578-km diameter asteroid has a metallic core (164 km), a dunite mantle (165 km thick) and a basaltic crust (42 km thick) [after Ruzicka *et al.*, 1997]. The horizontal rows are all at the same times, and the columns represent slices through the asteroid. (A,B) 2D slice parallel to the trajectory in the center plane of the sphere, (C,D): 2D slice perpendicular to the trajectory in the plane of the impact point. (A,C) show the maximum tensile stress experienced by the target throughout the evolution; (B,D) show the magnitude of the shear stress (represented by the second invariant of the deviatoric stress tensor, J2P). The white outlines show regions of maximum tensile stress. The mantle is considered fractured when local stress exceeds the

overburden by 180 MPa [Cohn and Ahrens, 1981 (this occurs at the transition from cyan to green).

Figure 12. The same parameters as in Figure 11, revealing the later evolution of subsurface damage. The black arrows in A and C indicate regions of failure.

Figure 13. Schematic showing how the angle α is defined: the angle between the normal to the line connecting the impact point and its antipode (purple) and the orientation of the “petal” failure planes.

Figure 14. Images of the grooves on Vesta from the Dawn spacecraft. A) Image of the full asteroid, taken at a distance of 5,200 km, showing equatorial grooves (black arrow); B) Image of Vesta showing grooves near the north pole (black arrow). The image was taken by the Dawn spacecraft at a distance of 5,200 km. Resolution is ~500 m/pixel; C) Close-up view of Vesta’s equatorial grooves. Image credits: NASA/JPL-CalTech/UCA/MPS/DLR/IDA.

Figure 15. Global map of the giant asteroid Vesta composed from images from the Dawn framing camera. The two sets of grooves are indicated by white arrows. They cross-cut each other near the equator between 300-330°. The equatorial grooves cut the north-pole grooves, indicating that they’re younger. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLA/IDA.

Figure 16. Elevation map of Vesta’s south pole, showing the large impact crater Rheasilvia (outlined). Rheasilvia has a diameter of 460 km (80% of the asteroid) and partially obscures an older impact crater. The central mound is approximate 23 km high and 200 km wide. White arrows locate the equatorial grooves. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLA/IDA.

Figure 17. Inferred impact points at two different impact angles based the angle between the center of the crater structure and the impact point as measured in laboratory experiments. The white dashed line indicates an assumed spherical shape for Vesta with a 289-km radius. The blue lines point to the crater center antipode, and the green lines show the impact point and its antipode. A) Inferred impact point for 40° impact; B) view of the south pole of Vesta showing inferred impact point from A. Direction and impact point indicated by the white arrow; C) Inferred impact point for a 65° impact shown by the tip of the arrow; D) View of the south pole of Vesta showing the estimated impact point from panel C. Images were taken from an animation showing the surface structure of Vesta as observed by the Dawn spacecraft. Image credit: NASA/JPL-Caltech/UCLA/MPS/DLA/IDA.

FIGURES

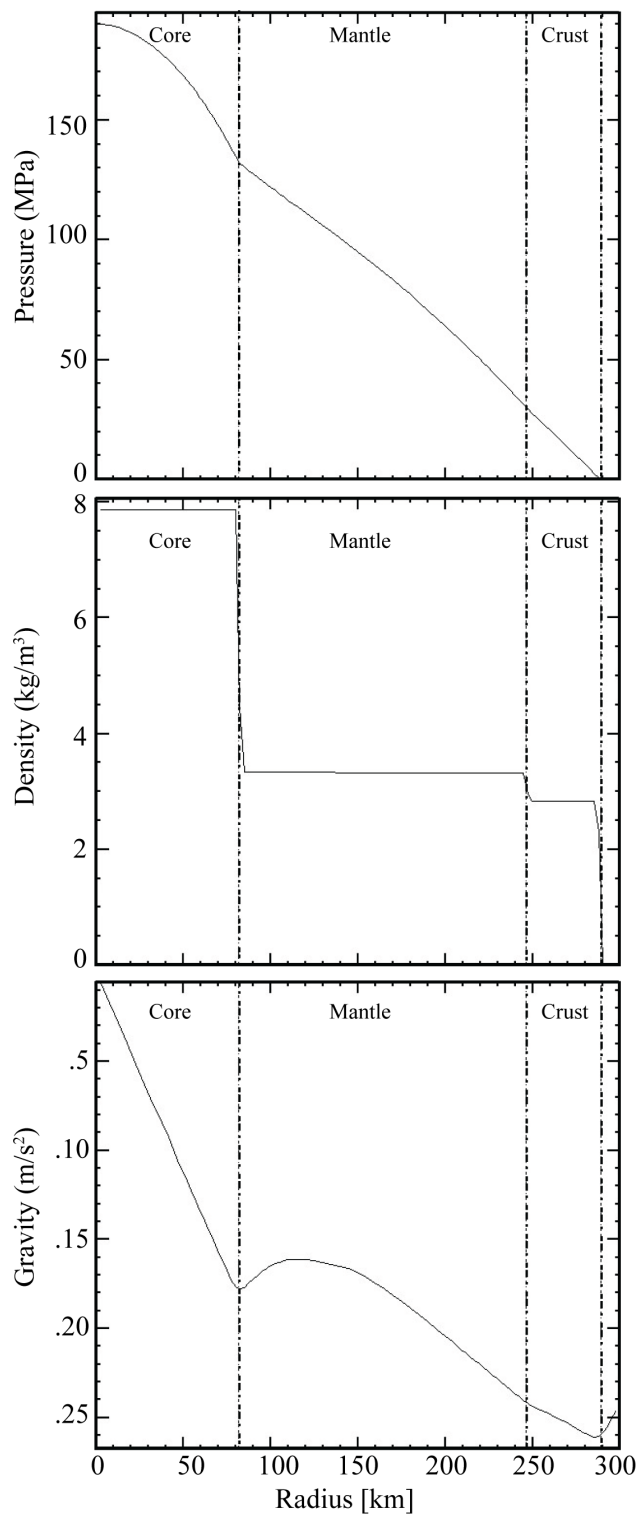


Figure 1

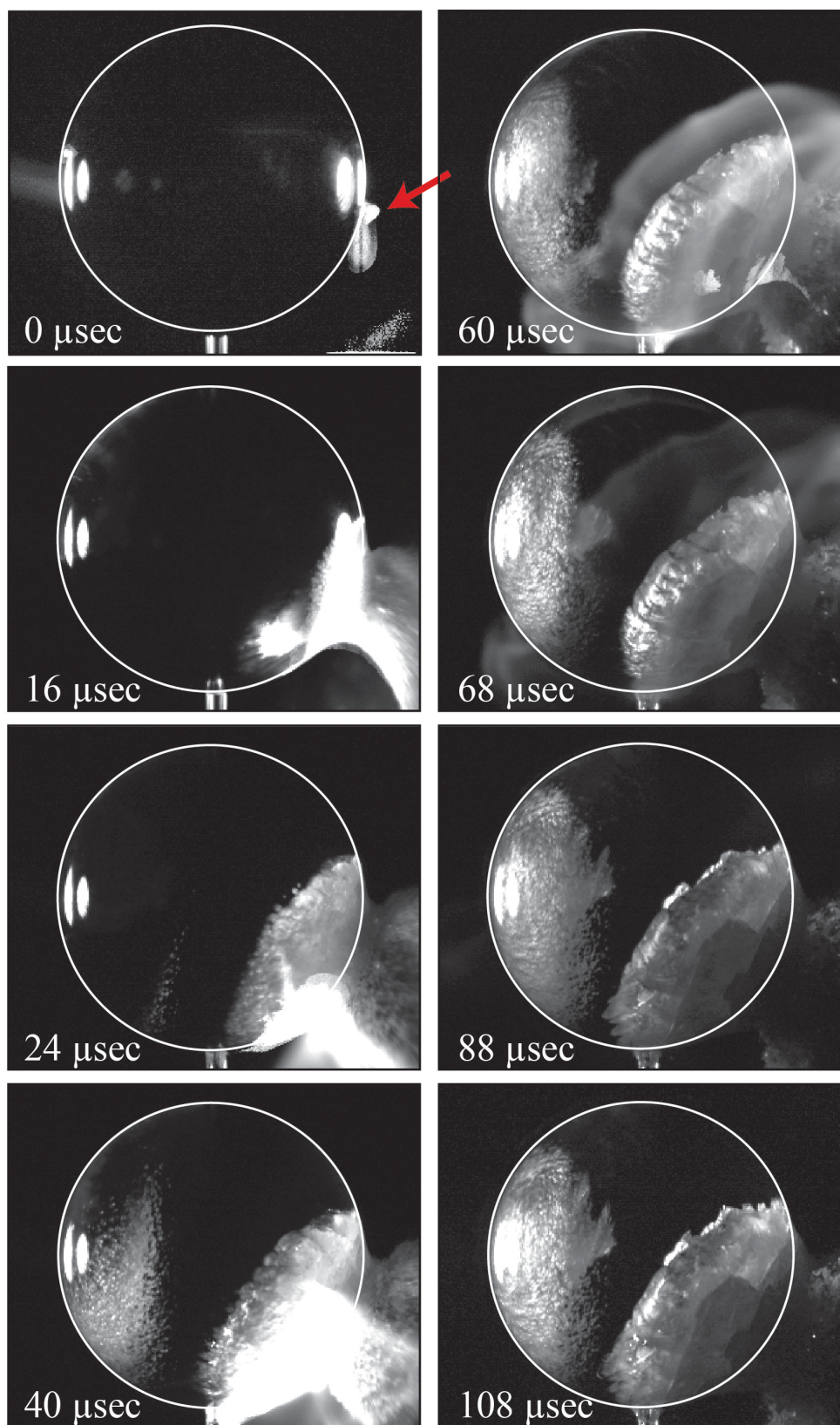


Figure 2



Figure 3

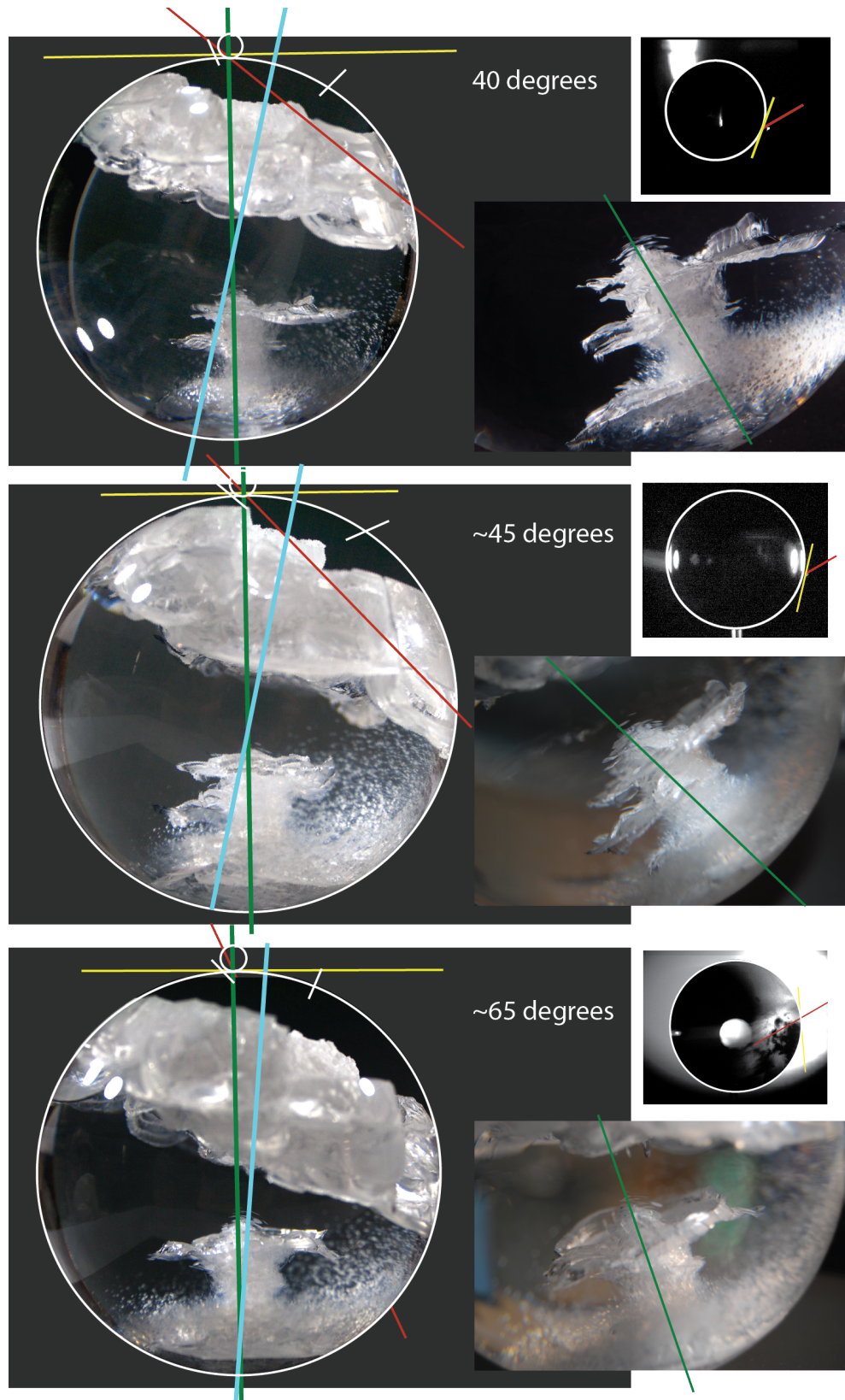


Figure 4

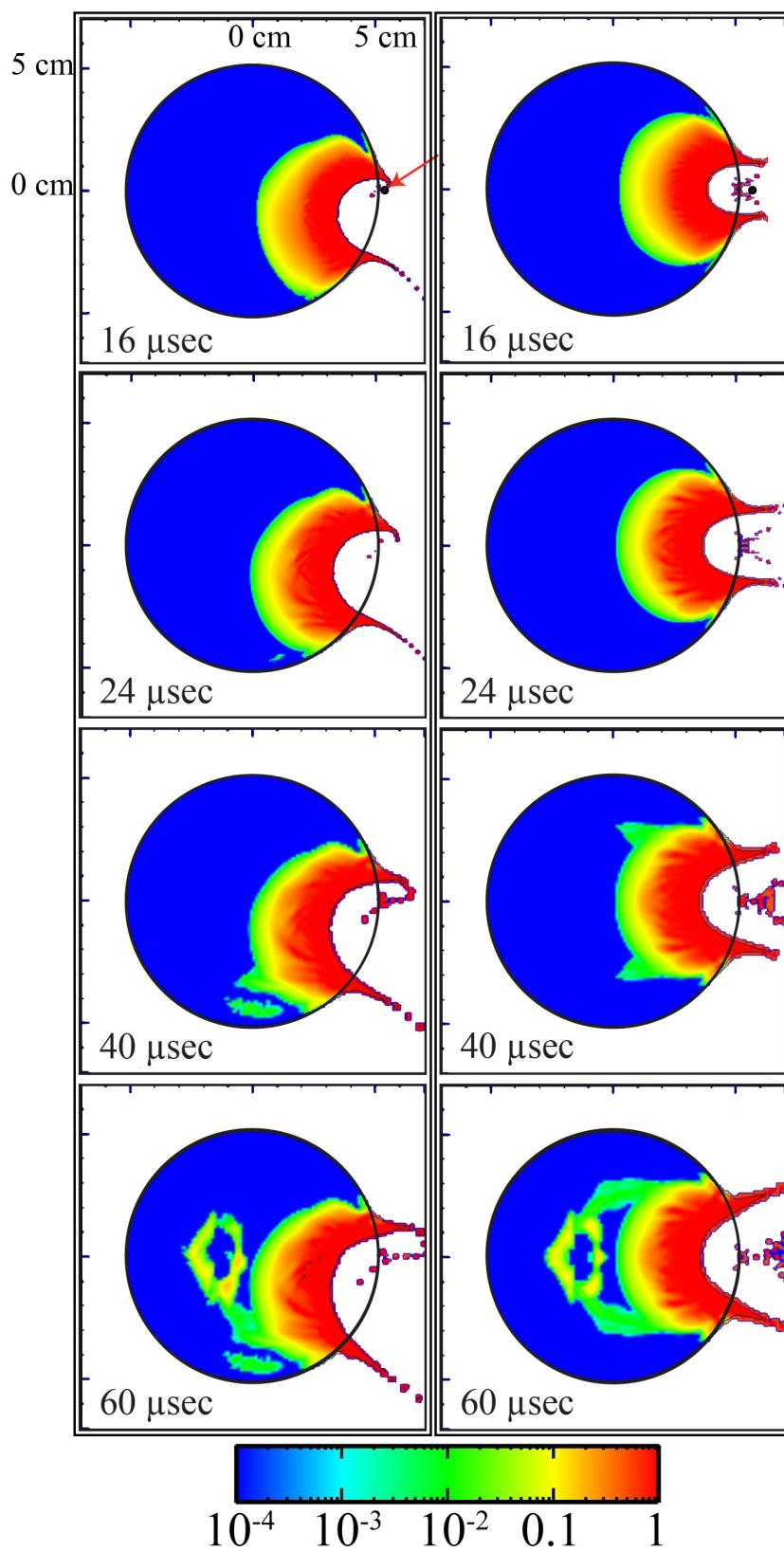


Figure 5

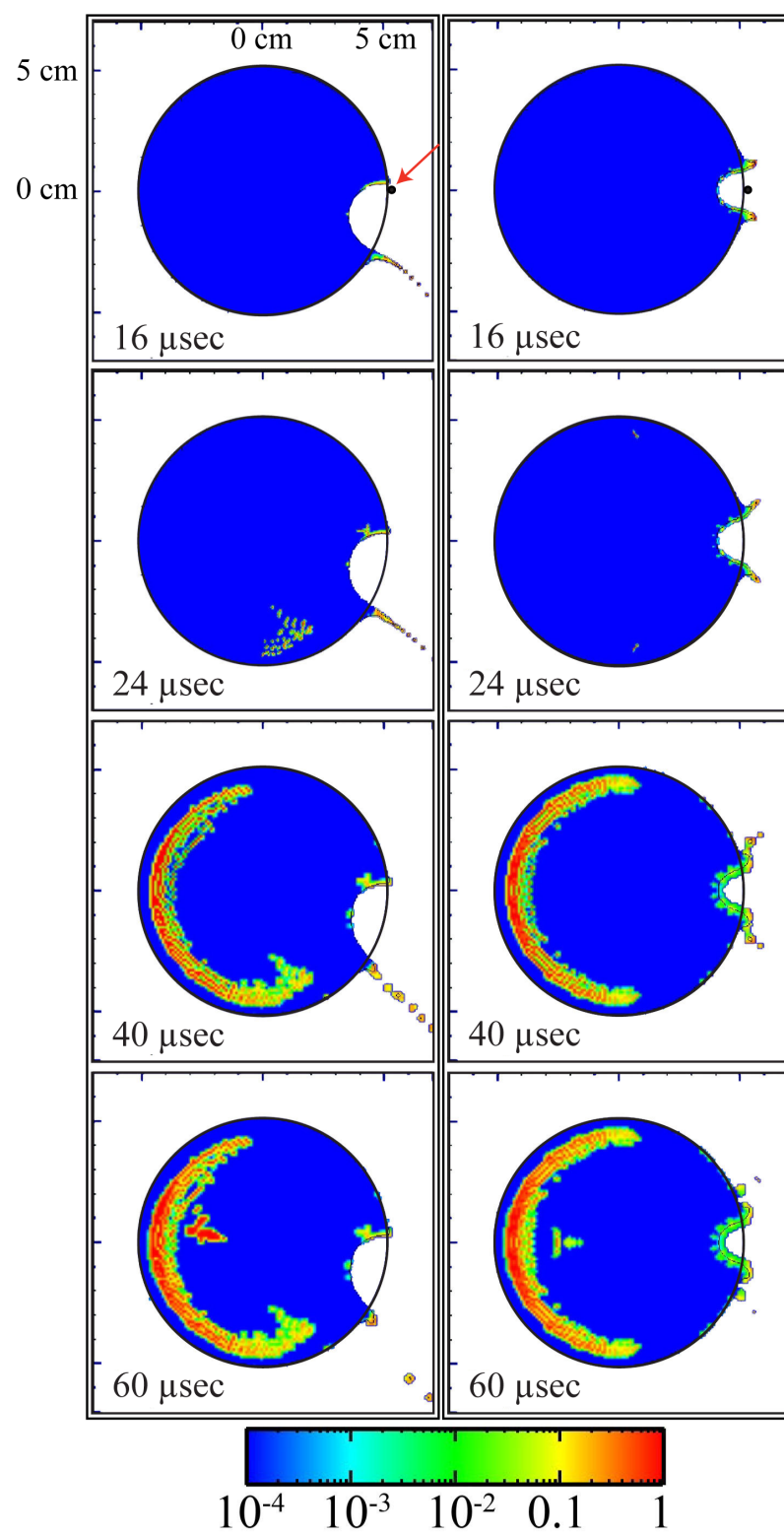


Figure 6

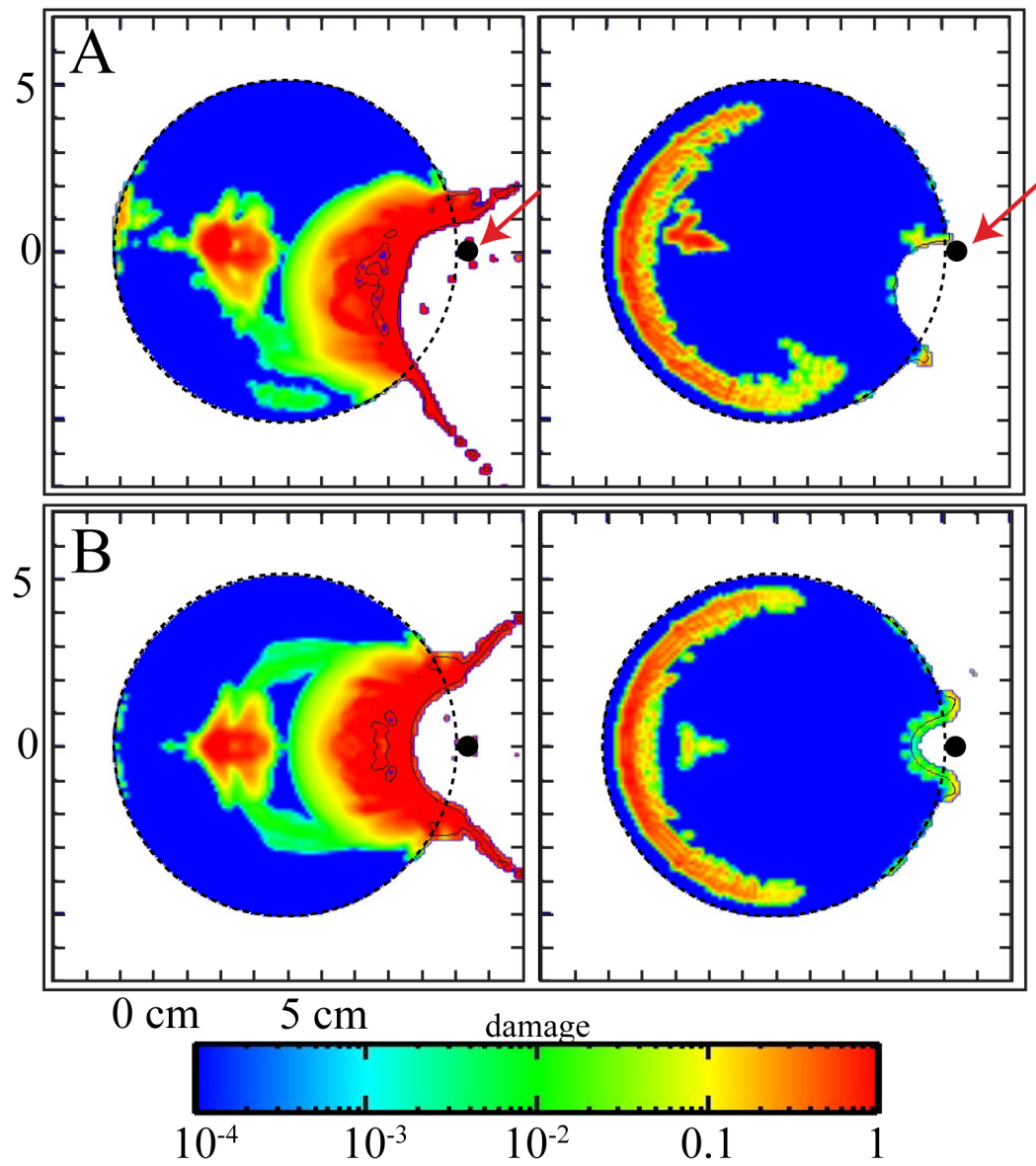


Figure 7

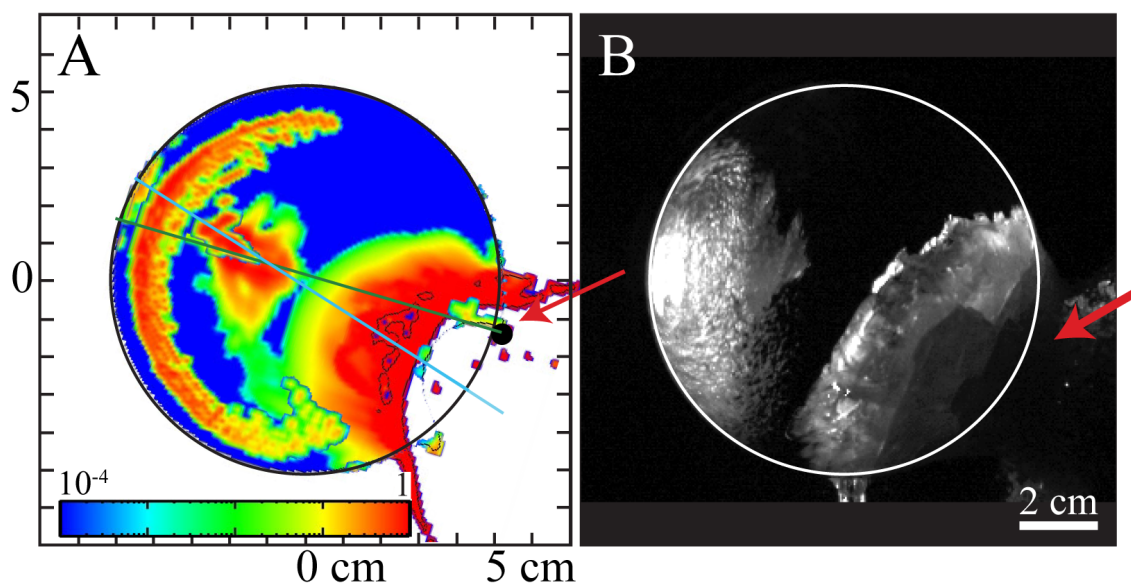


Figure 8

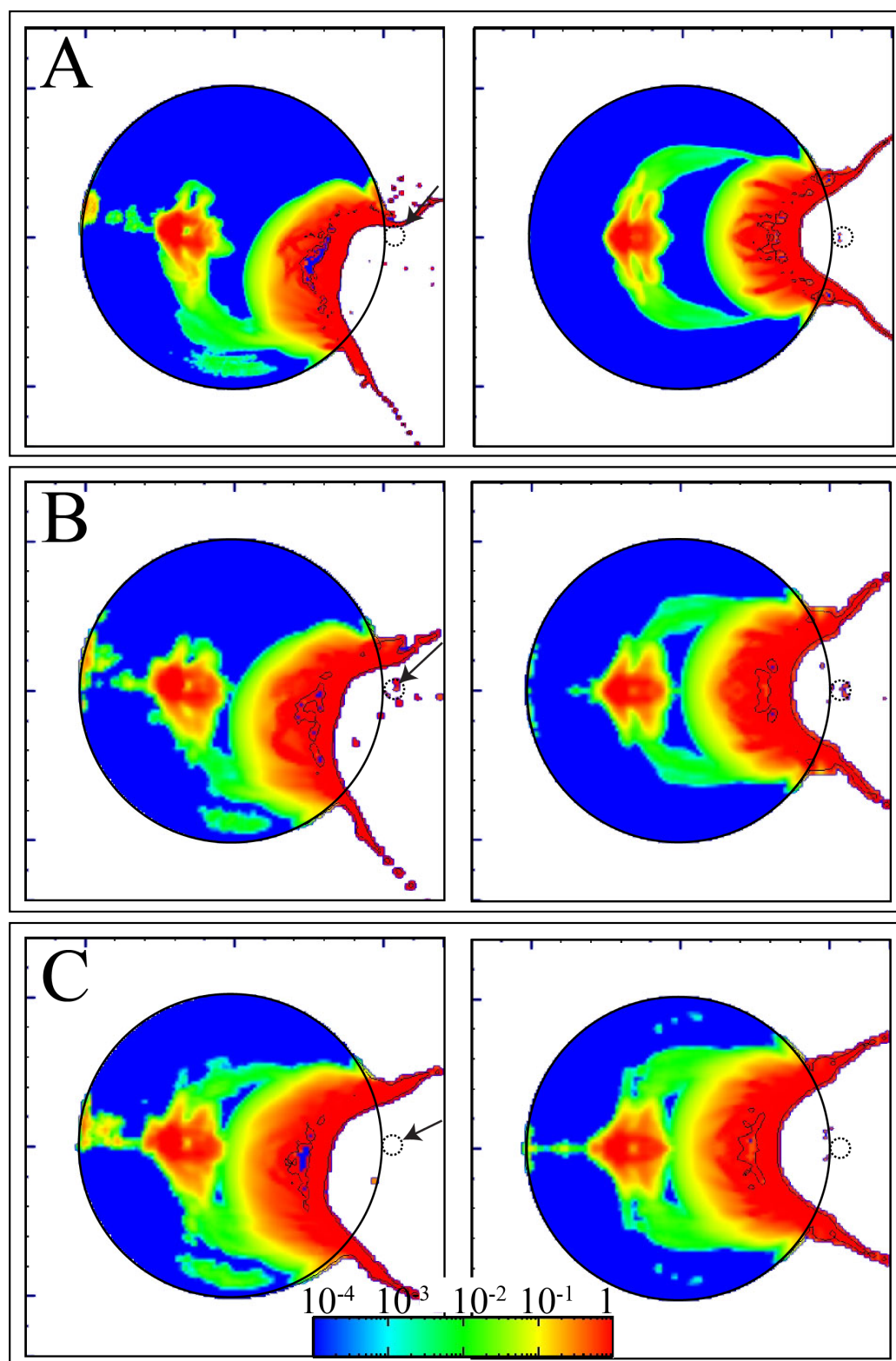


Figure 9

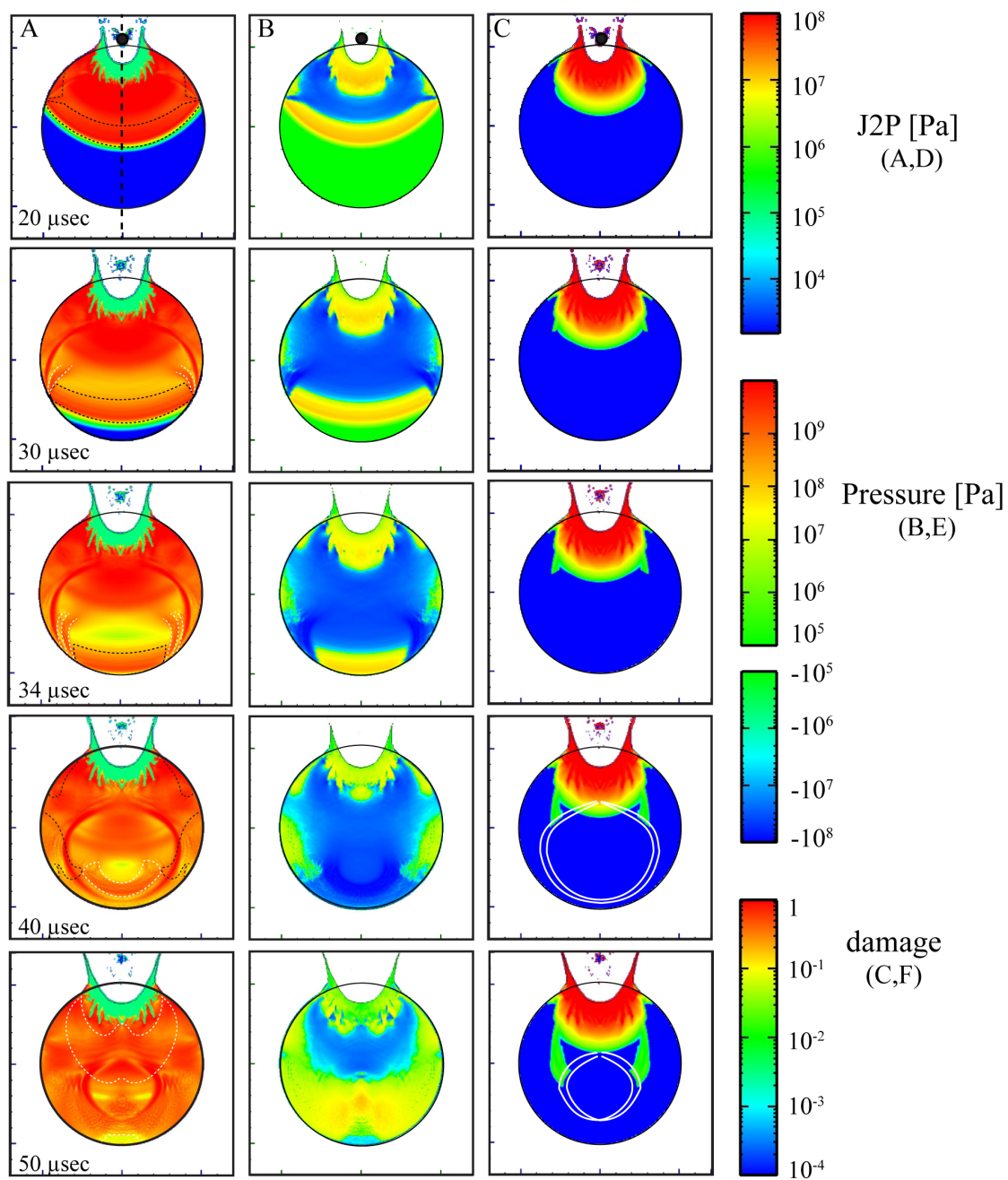


Figure 10 (a-c)

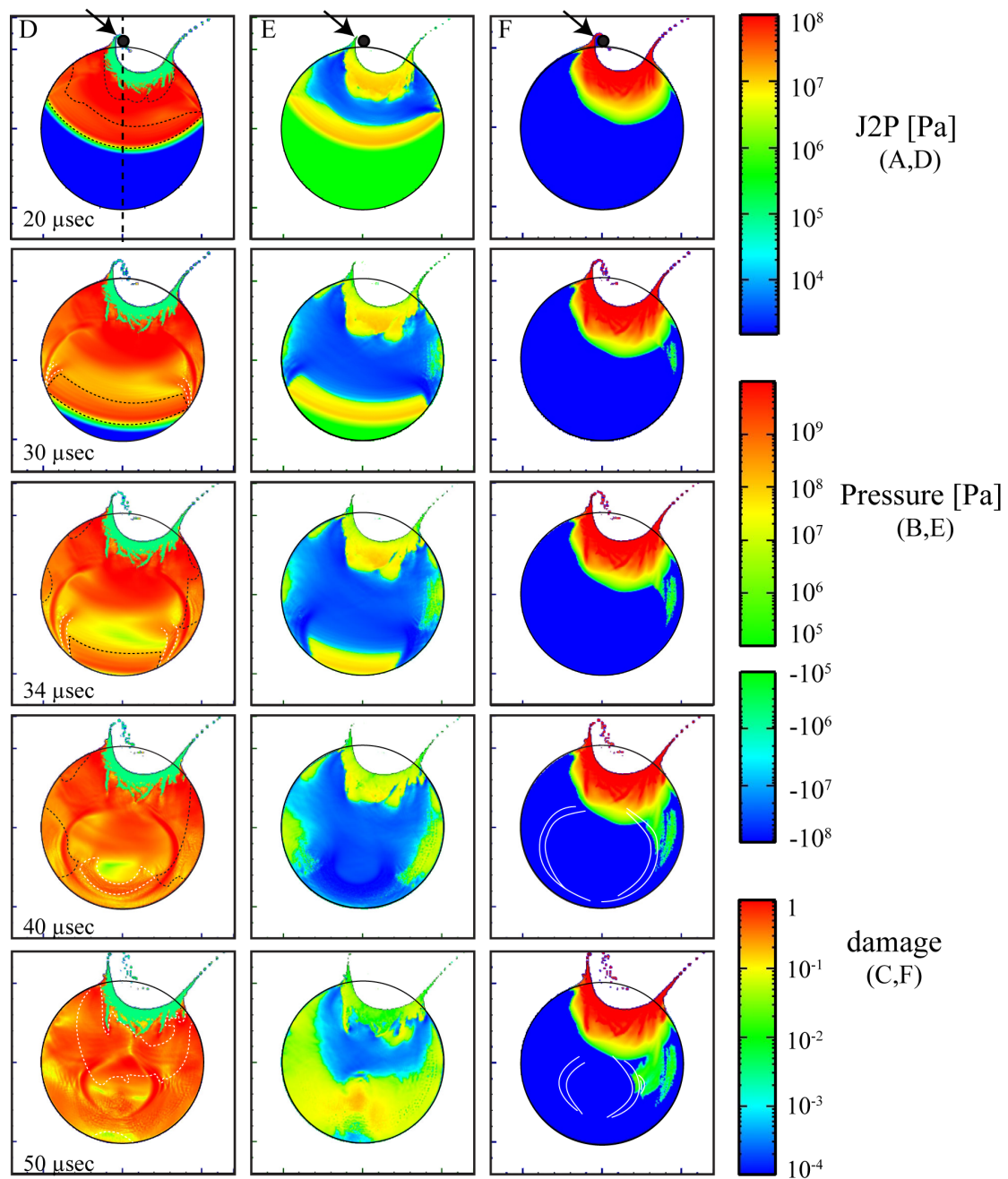


Figure 10 (d-f)

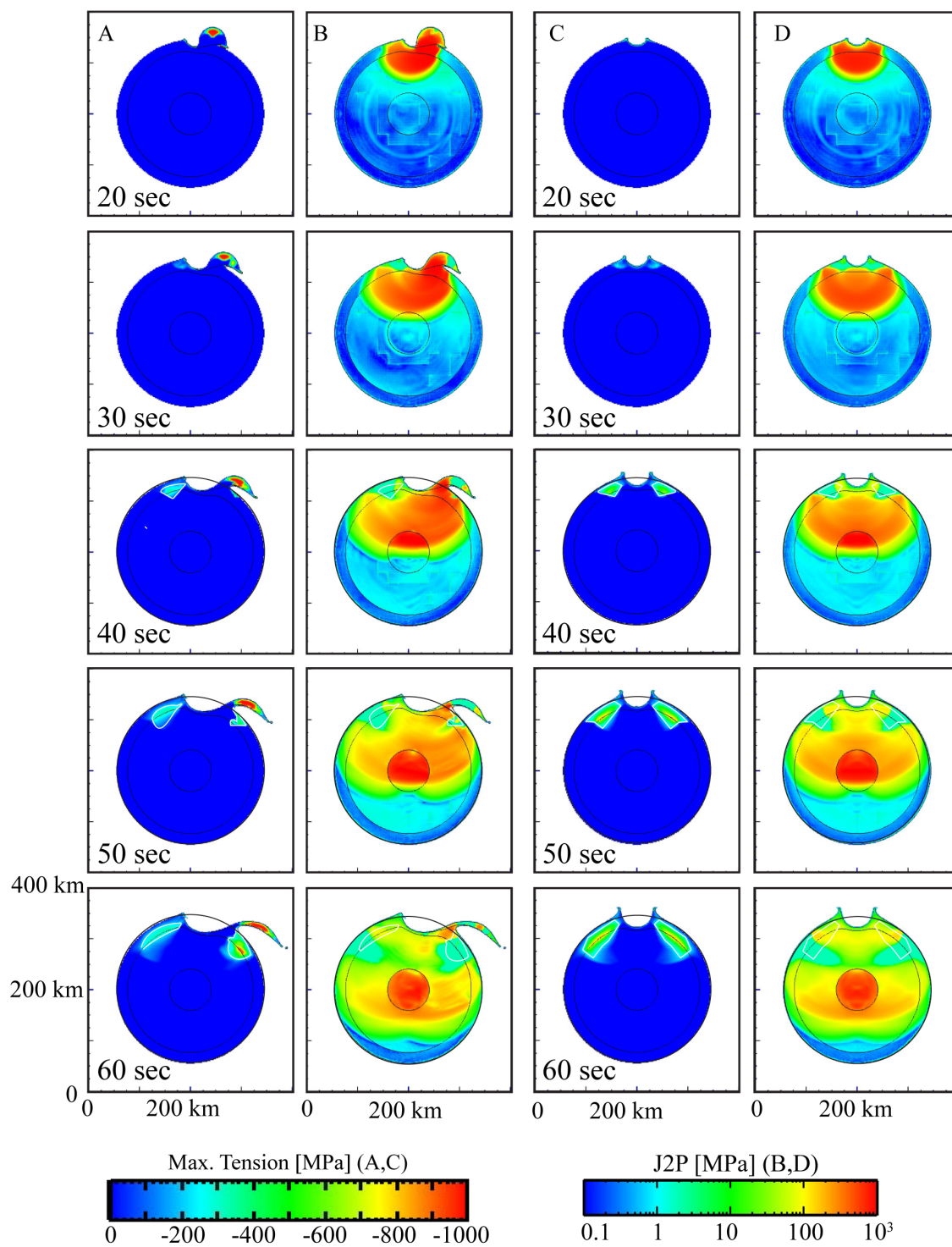


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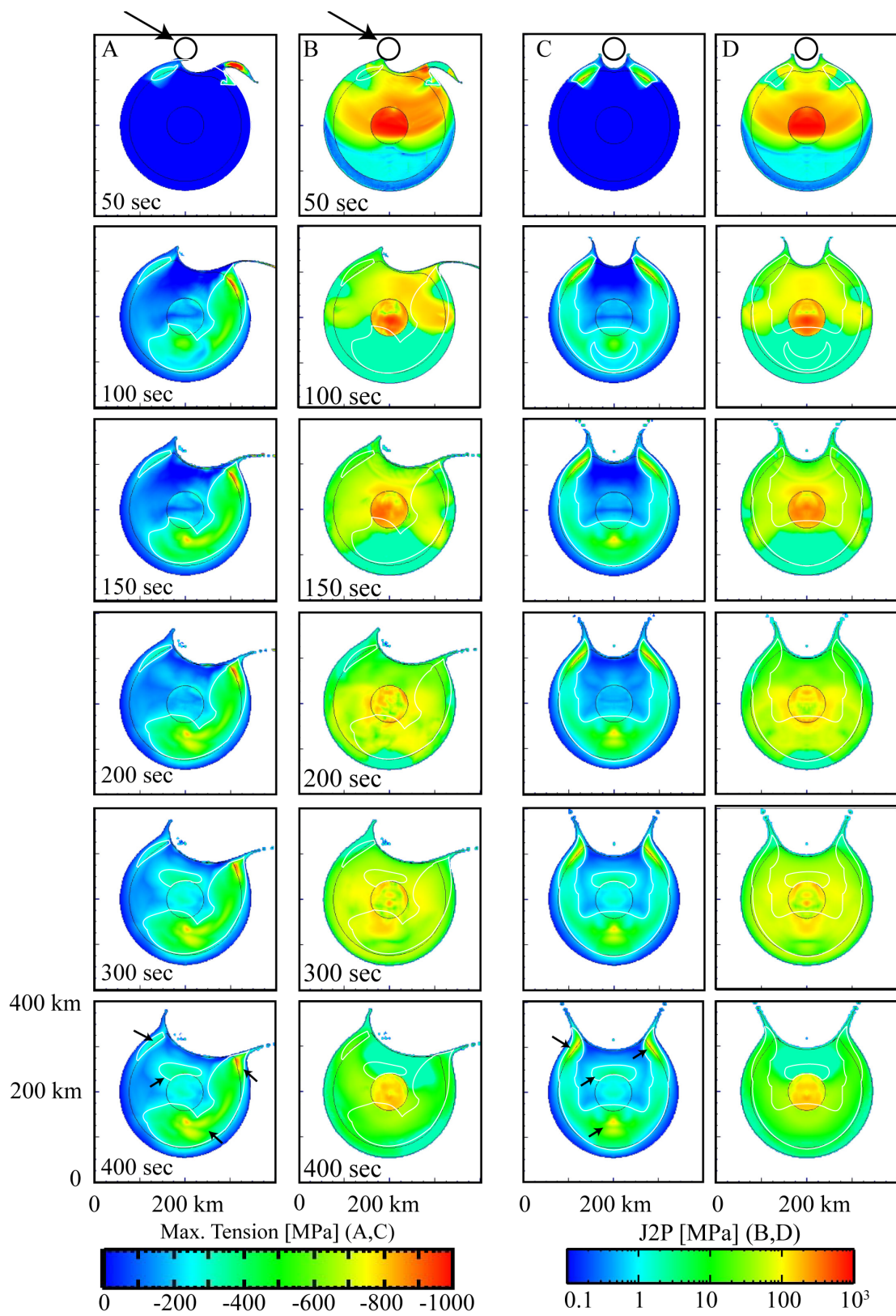


Figure 12

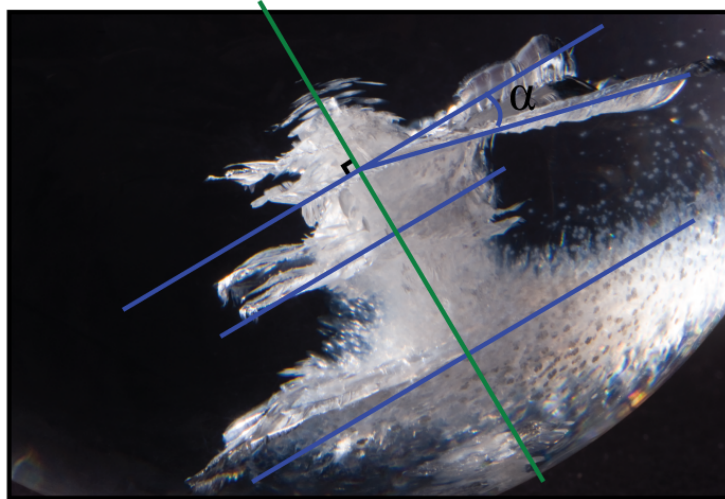


Figure 13

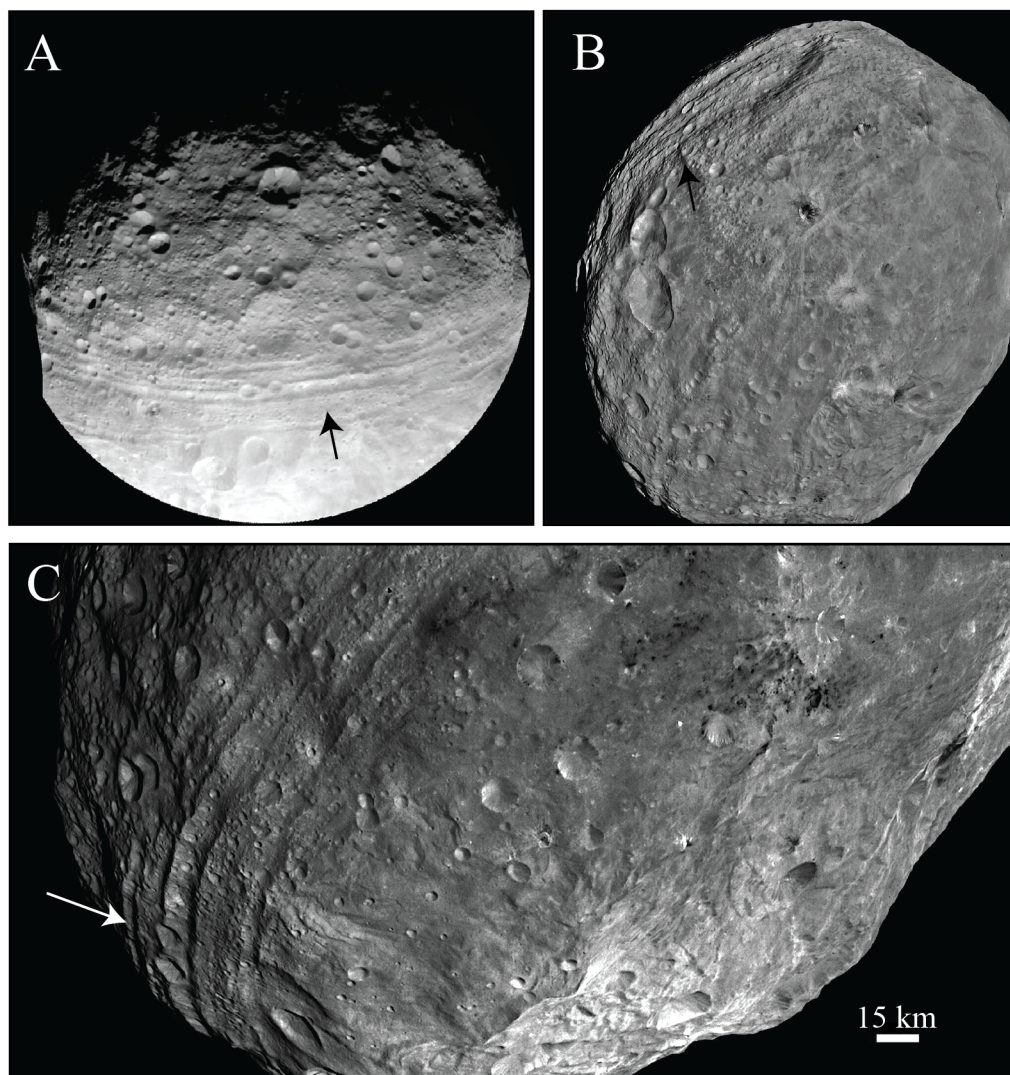


Figure 14

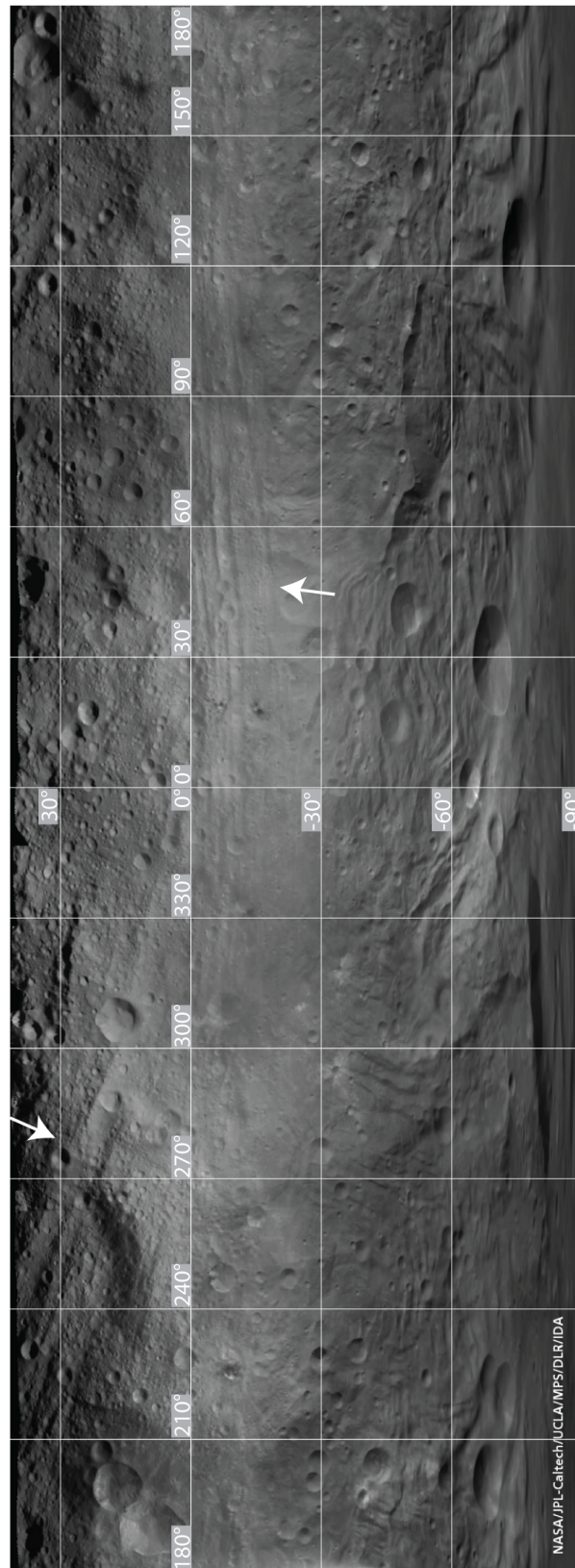


Figure 15

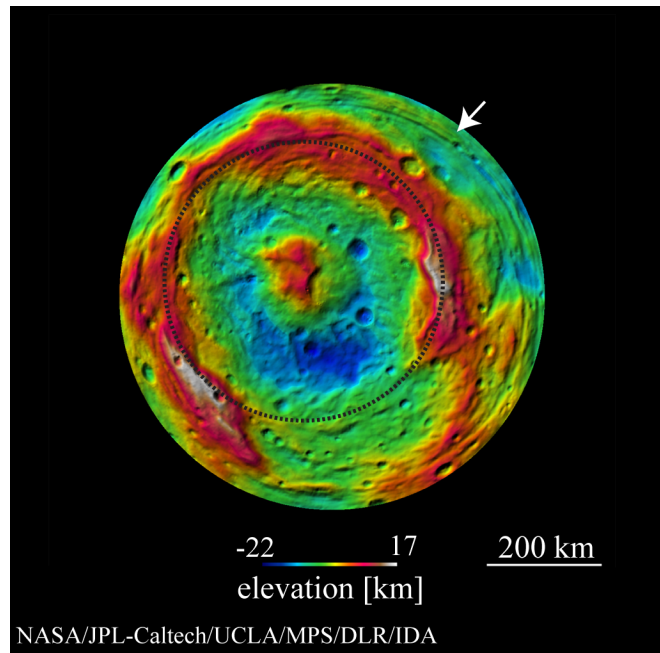


Figure 16

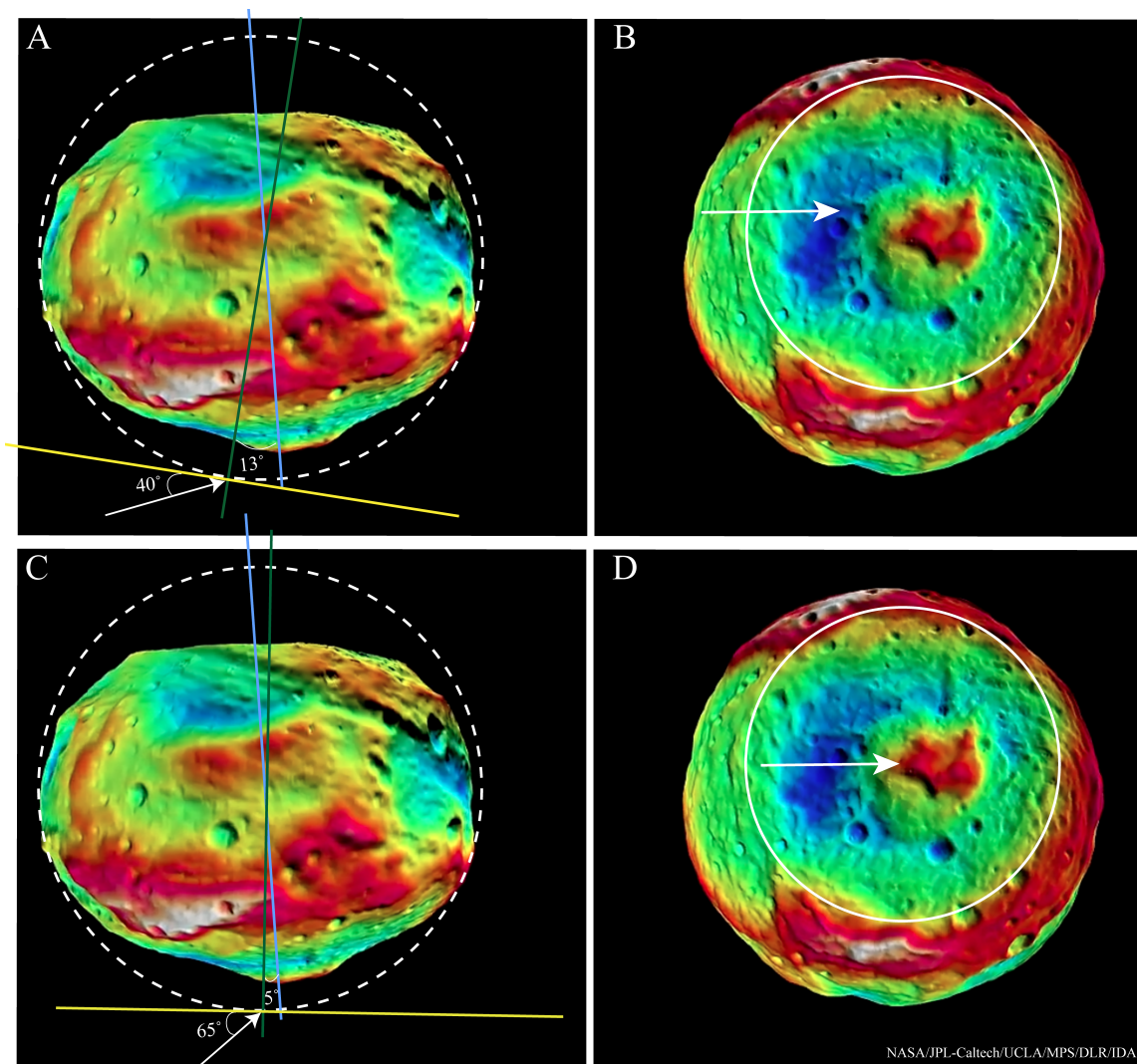


Figure 17