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## **Benchmarking impact hydrocodes in the strength regime: implications for modeling deflection by a kinetic impactor**

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1 **Abstract**

2 The Double Asteroid Redirection Test (DART) is a NASA-sponsored mission that will be the first  
3 direct test of the kinetic impactor technique for planetary defense. The DART spacecraft will  
4 impact into Didymos-B, the moon of the binary system 65803 Didymos and the resulting period  
5 change will be measured from Earth. Impact simulations will be used to predict the crater size and  
6 momentum enhancement expected from the DART impact. Because the specific material  
7 properties (strength, porosity, internal structure) of the Didymos-B target are unknown, a wide  
8 variety of numerical simulations must be performed to better understand possible impact  
9 outcomes. This simulation campaign will involve a large parameter space being simulated using  
10 multiple different shock physics hydrocodes. In order to understand better the behaviors and  
11 properties of numerical simulation codes applicable to the DART impact, a benchmarking and  
12 validation program using different numerical codes to solve a set of standard problems was  
13 designed and implemented. The problems were designed to test the effects of material strength,  
14 porosity, damage models, and target geometry on the ejecta following an impact and thus the  
15 momentum transfer efficiency. Several important results were identified from comparing  
16 simulations across codes, including the effects of model resolution and porosity and strength model  
17 choice: 1) Momentum transfer predictions almost uniformly exhibit a larger variation than  
18 predictions of crater size; 2) The choice of strength model, and the values used for material  
19 strength, are significantly more important in the prediction of crater size and momentum  
20 enhancement than variation between codes; 3) Predictions for crater size and momentum  
21 enhancement tend to be similar (within 15-20%) when similar strength models are used in different  
22 codes. These results will be used to better design a modeling plan for the DART mission as well  
23 as to better understand the potential results that may be expected due to unknown target properties.  
24 The DART impact simulation team will determine a specific desired material parameter set  
25 appropriate for the Didymos system that will be standardized (to the extent possible) across the  
26 different codes when making predictions for the DART mission. Some variation in predictions  
27 will still be expected, but that variation can be bracketed by the results shown in this study.

28  
29 **1. Introduction**

30 The Double Asteroid Redirection Test (DART) is a NASA-sponsored mission, currently in Phase  
31 C development (as of January, 2019). DART is the first direct test of kinetic impactor technology  
32 for planetary defense, and involves the impact of a spacecraft into the moon of a binary system in  
33 order to monitor momentum transfer to the target. High-fidelity impact simulations are one tool  
34 used to better predict the results of this impact. Because the target of the DART impact is a binary  
35 system that has not previously been visited by spacecraft, many of the target properties are  
36 unknown and the potential modeling parameter space is large. To deal with this, several different  
37 hydrocodes are employed by the team to examine possible effects. This variety of hydrocodes  
38 comes with some uncertainty, however, as different codes utilize different numerical techniques  
39 and material model implementations. In order to understand better the behaviors and properties of  
40 numerical simulation codes applicable to the DART impact, a benchmarking and validation  
41 program using different numerical codes to solve a set of standard problems was designed and  
42 implemented. The problems are designed to test the effects of material strength, porosity, damage  
43 models, and target geometry on the ejecta following an impact and thus the momentum transfer  
44 efficiency. Here, we briefly introduce the DART mission concept, kinetic impactors for planetary  
45 defense, the hydrocode benchmarking campaign performed by the DART team and collaborators,

46 and the codes used in this study. This is followed by the results of five different benchmarking  
47 cases and implications of these comparisons for the impact modeling DART working group.  
48

### 49 *1.1 The Double Asteroid Redirection Test*

50 Approaches to asteroid impact mitigation fall into four broad categories [Board et al., 2010]:  
51 civil defense, slow-push/pull methods, kinetic impact, and nuclear detonation. These approaches  
52 are differently suited to various impact scenarios, and they are roughly listed in order of increasing  
53 impactor size and decreasing warning time. Deflection by nuclear device has been shown by  
54 extensive numerical simulation to be effective against NEOs as large as 1 km in diameter. Testing  
55 this method on an asteroid is not necessary, due to its effectiveness and the availability of extensive  
56 test history data. The next-most potent mitigation technique, the kinetic impactor, is untested in  
57 the regimes where it would be of most use: objects of ~100-300 m diameter. Kinetic impactors are  
58 conceptually simple: a mass is thrown at a threatening object and the added momentum of the mass  
59 changes the threat's orbit such that impact with Earth is avoided. Given decadal-scale warning  
60 times, imposed speed changes of mm/s to cm/s scales are sufficient for a successful mitigation.

61 To understand the effectiveness of a kinetic impactor, we are reliant upon impact and shock  
62 physics codes that are calibrated to laboratory experiments many orders of magnitude smaller in  
63 size than a real-world application. Some of the most important questions about the technique,  
64 including how much momentum is carried away from the impact by ejecta, and how much the  
65 target's orbit is affected, remain unanswered.

66 NASA's Double Asteroid Redirection Test (DART) [Cheng et al., 2018] is a planetary defense  
67 demonstration mission intended to carry out a kinetic impactor test against a representative target  
68 (e.g., one similar to many Potentially Hazardous Asteroids (PHAs)). DART is planned to visit  
69 (65083) Didymos, a binary asteroid system with components ~780 m and ~150 m in diameter  
70 (informally called "Didymos A" and "Didymos B") [Naidu et al., 2016]. DART will impact  
71 Didymos B at ~6 km/s, changing its orbit period, currently 11.9 hours, by up to several  
72 minutes. This period change will manifest in a change in the lightcurve of the Didymos system,  
73 in particular a shift in the timing of eclipses and occultations of Didymos A by Didymos B and  
74 vice versa. Because the period change is observable in the lightcurve, the required post-impact  
75 observations can be made with ground-based telescopes, and the amount of period change can be  
76 used to measure the change in speed of Didymos B caused by the DART impact. The spectral  
77 characteristics of Didymos A classify the asteroid as an S-type, a type associated with ordinary  
78 chondrite meteorites [Dunn et al., 2013], the most common meteorite type seen to fall to Earth,  
79 and Didymos B is believed to be composed of similar material (if it co-accreted or formed after  
80 rotational disruption of the primary [Walsh et al., 2012]). Didymos is both representative of the  
81 population of the most likely impactors and also allows modeling efforts to use a very well-known  
82 and common material as the target.  
83

### 84 *1.2 Momentum Enhancement by Kinetic Impactor*

85 The efficiency of deflection from a kinetic impactor is often measured using the momentum  
86 enhancement factor,  $\beta$ , which defines the momentum imparted to the asteroid by impact in terms  
87 of the momentum of the impactor.  $\beta$  is defined as:

$$88 \quad \beta = \frac{p_{\text{target, post deflection}}}{p_{\text{impactor}}} \quad (\text{Eq. 1})$$

89 where the momentum of the target (here, Didymos-B) post-impact is  $p_{\text{target, post deflection}} = \text{mass}_{\text{target, post}}$   
90  $\text{deflection} * \Delta v_{\text{target}}$ , with  $\text{mass}_{\text{target, post deflection}} = \text{mass}_{\text{target, initial}} + \text{mass}_{\text{impactor}}$  and the incoming  
91 momentum of the impactor ( $p_{\text{impactor}}$ ) is equal to the DART spacecraft momentum. Here, the mass

92 of Didymos-B is estimated from the observed size of Didymos-B and assumed material properties,  
93 and  $\Delta v_{\text{target}}$  is the determined from the measured period change. For a general impact simulation,  
94 the initial projectile momentum and the mass of the target are inputs to the model and  $\Delta v_{\text{target}}$  is  
95 calculated from the simulation results. Determining  $\beta$  from the DART impact is one the mission's  
96 top level requirements.

### 97 98 *1.3 Impact Simulation and Modeling Working Group*

99 The Asteroid Impact and Deflection Assessment (AIDA) concept is an international  
100 collaboration framework between NASA and ESA. AIDA was originally composed of the AIM  
101 ESA mission [Michel et al., 2016], which is currently re-designed as the Hera mission [Michel et  
102 al. 2018] which will be proposed to ESA member states for funding at the ESA Council of  
103 November 2019, and the DART mission. As part of the collaboration, an international working  
104 group was formed to better understand the range of possible outcomes of the DART impact. DART  
105 will join Deep Impact [A'Hearn et al., 2005] and LCROSS [Colaprete et al., 2010; Schultz et al.,  
106 2010] as one of three full-scale planetary impact experiments, and is the only one in which the  
107 deflection of the target will be measured. The goals of this working group are to 1) better  
108 understand the magnitude of this deflection by determining the sensitivity of impact models to  
109 impact conditions, 2) determine the momentum transfer efficiency,  $\beta$ , from the deflection  
110 magnitude, and its sensitivity to target properties, and 3) predict the ejecta mass and putative crater  
111 size following the DART impact. All three goals require numerous impact simulations, and will  
112 be accomplished using a variety of numerical approaches.

### 113 114 *1.4 Overview of Numerical Shock Physics Codes*

115 Simulations of dynamic processes require solving the equations of motion (conservation of  
116 mass, momentum and energy) for a given material. The set of equations is closed using a  
117 constitutive model. All shock physics codes, which are used to simulate impact processes, solve  
118 similar forms of the conservation equations. Constitutive models, however, can vary widely.  
119 Typically, a constitutive model is separated into two parts: the volumetric response of the material  
120 summarized by a material's Equation of State (EOS), and the response to deviatoric strains  
121 summarized by a strength model. The accuracy of the model predictions depends on how  
122 accurately the material models (EOS + strength) replicate material behavior, and how well known  
123 the properties included in those models are. Though the conservation equations are consistent  
124 across numerical implementations, how they are solved can vary. There are two main methods for  
125 solving the equations of motion: an *Eulerian* solution and a *Lagrangian* solution. Both methods  
126 have historically been used to produce reliable and robust shock codes.

127 The Eulerian solution treats continuum variables (i.e., density, temperature) from a fixed frame  
128 of reference. Equations of motion and conservation are solved using a mesh fixed in space so that  
129 material moves relative to the mesh. One benefit of the Eulerian method is that it does not suffer  
130 from mesh entanglement or oddly-shaped elements. However, Eulerian meshes have historically  
131 had difficulty tracking material interfaces, and in a given simulation many cells may include  
132 multiple materials; these are called "mixed cells". Mixed cells require averaging of material  
133 properties and state variables within the cell, which can lessen the accuracy of the model's  
134 prediction. Many techniques have been developed to try to deal with this. One such method is  
135 adaptive mesh refinement (AMR), which allows areas of high-resolution to be strategically  
136 generated within the model that allow better tracking of the shock front and of material interfaces.  
137 These regions, and the criteria for increased mesh resolution, are usually pre-defined by the user,

138 and defining appropriate metrics is not always straightforward. These criteria must be carefully  
139 chosen in order to avoid introducing other systematic errors into the calculation.

140 In contrast, the Lagrangian method treats continuum variables from a frame of reference fixed  
141 with respect to the material. Equations of motion and conservation are solved using a mesh fixed  
142 with respect to the material so that the mesh moves through space and deforms along with the  
143 material. In general, this can be computationally more efficient than Eulerian solutions. However,  
144 care must be taken that the mesh does not distort to the extent that numerical approximations are  
145 significantly affected. A variety of approaches has also been developed to deal with strongly  
146 distorted meshes. A hybrid approach, which is popular, is referred to as Arbitrary Lagrangian  
147 Eulerian (ALE), which allows the computation to remain Lagrangian until some specified  
148 condition is met. When that happens, the mesh is allowed to relax according to specified rules as  
149 material advects through it. Here, the term “Eulerian” is used to describe this advection process,  
150 not necessarily a static grid. Other approaches involve converting strongly distorted elements into  
151 Smooth Particle Hydrodynamic (SPH) particles and allowing them to move freely within the mesh.

152 Meshless Lagrangian methods, such as Smooth Particle Hydrodynamics (SPH) and its adaptive  
153 versions (e.g., Spheral) use interpolation nodes (particles) to calculate values for parameters of  
154 interest. These particles interact through a “kernel function” that has a characteristic radius known  
155 as the “smoothing length”. The physical quantity of any given particle is obtained by summing the  
156 relevant properties of all the particles that lie within the range of the kernel. Because there is no  
157 mesh, SPH methods are well-suited to simulate problems with large amounts of deformation,  
158 complex boundary dynamics, or for problems where material expands into large volumes. SPH  
159 codes can be quite computationally expensive, however, and treating boundary conditions is not  
160 always as straightforward as in a gridded code.

161

### 162 *1.5 Sources of Code Variability*

163 Variability in code results may arise from the way in which the flow equations are discretized  
164 and solved, which differs between codes. Pierazzo et al (2008) performed a study validating 8  
165 numerical approaches against each other by looking at impacts into strengthless targets. This initial  
166 benchmarking campaign showed some variability in code results stemming from solution  
167 algorithms, stability parameters within the codes, and resolutions. For instance, predictions of peak  
168 pressures, crater depth, and diameter varied by 10-20% between codes. Additional complicating  
169 factors beyond those examined in detail during this initial study, like the effect of material models  
170 and how solids behave when they have some strength, are also likely to be important and lead to  
171 variation in simulation results.

172 Strength models are used to simulate departures of material response from strictly  
173 hydrodynamic behavior. Specific material properties will govern how a material behaves in  
174 response to stress, which ultimately leads to differing behaviors of different materials for the same  
175 impact conditions. The accuracy of the EOS is especially important early in an impact calculation,  
176 when the peak pressures are high and material strength becomes less important near the impact  
177 point. As the impact progresses, however, and deformation occurs farther from the point of first  
178 contact, material strength (described by the constitutive equation, or, colloquially, material model),  
179 becomes important for the cratering process and crater formation. High-fidelity models of material  
180 behavior can include things such as, e.g., strain hardening behaviors, rate effects, temperature  
181 effects (e.g., thermal softening), porosity, etc. In mechanical testing, geologic materials, including  
182 meteoritic material, exhibit all of the above effects, including rate- and temperature-dependent  
183 plasticity, and porosity effects [e.g., Kimberley and Ramesh, 2011; Buhl et al., 2013; Zwiessler et

184 *al.*, 2017; *Winkler et al.*, 2018]. How (and if) these effects are accounted for in the numerical codes  
185 will affect the predicted impact response of a material. The challenge is to pick appropriate material  
186 models that include relevant physics and deformation mechanisms for the materials and problem  
187 of interest.

188 In addition to these physical factors, results can also be affected by strictly computational  
189 factors. The grid resolution of a given simulation will affect the calculated magnitude of energy  
190 deposited into the target during an impact and how that energy propagates through the system.  
191 Parameters that are calculated during the simulation are averaged over a given cell (for grid-based  
192 solutions), thus a larger cell size (or a lower resolution) will result in increased averaging of  
193 parameters across the spatial domain. Therefore, a larger cell size provides less accurate  
194 parameters reported for a specific location in the target, and resolution should be closely tracked  
195 in simulations. For this study, convergence studies were performed for all of the codes. In impact  
196 cratering studies, spatial resolution is often reported in terms of “cells per projectile radius” (cpr),  
197 or equivalent. For codes that have adaptively refining mesh (e.g., CTH), the resolution reported is  
198 the resolution corresponding to the most highly-refined mesh. For the tests reported here, all  
199 projectiles have a diameter of ¼” (6.35-mm). Thus, a resolution of 5 cpr corresponds to a cell  
200 size of 0.125 cm, and a resolution of 10, 20, 45, 60 cpr correspond to cell sizes of 0.0625, 0.031,  
201 0.007, and 0.005 cm, respectively.

202

### 203 *1.6 The AIDA/DART Benchmarking and Validation Program*

204 In order to understand better the behaviors and properties of numerical simulation codes  
205 applicable to the DART impact, a benchmarking and validation program using different numerical  
206 codes to solve a set of standard problems was designed and implemented. The problems are  
207 designed to test the effects of material strength, porosity, damage models, and target geometry on  
208 the ejecta following an impact and thus the momentum transfer efficiency. They include  
209 simulations of a sphere impacting into a strengthless aluminum target, a strengthless basalt target,  
210 an aluminum target with a constant strength (which is easily implementable across codes) and a  
211 basalt target with strength, damage, and porosity. A more complicated model, of a basalt sphere  
212 impacting a larger basalt sphere is also simulated. All models include standardized equations of  
213 state, but, in general, strength and plasticity models are allowed to vary between codes and users.

214

## 215 **2. Methods**

216 Impact modeling by numerical simulations is a crucial approach used to interpret the results of the  
217 DART kinetic impact deflection experiment, to infer physical properties of the target asteroid, and  
218 to advance understanding of impact processes on asteroids. Several distinct types of numerical  
219 methods can be used to model the DART deflection experiment, differing in the fundamental  
220 approaches to solving flow equations as well as in the modeling of target material properties and  
221 responses to impact stresses. Because of the differences in possible code design and method, a  
222 benchmarking and validation task was undertaken by the AIDA/DART Impact Modeling and  
223 Simulation Working Group in which different numerical codes were applied to solve a set of  
224 standard problems (Table 1). The results from these codes were then analyzed and compared to  
225 better understand the variability that might be expected in simulations relevant to DART.

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228 **Table 1.** Summary of the Impact Codes Used in the Study

Code name	Type of mesh	Characteristics	Key Code References
CTH	Eulerian, continuum representation of materials, Adaptive Mesh Refinement	<p>2D and 3D geometry 2-step Eulerian finite difference code Allows multiple materials and rheologies</p> <p>Strength/damage model usually employed: pressure-dependent yield with Johnson-Cook fracture model to track damage based on plastic strain (scalar damage model)</p> <p>Porosity: p-alpha porosity model</p>	McGlaun et al. 1990; Crawford et al. 1999
ASPH (Spherical)	Smooth Particle Hydrodynamics (meshless)	<p>2D and 3D geometry Adaptive SPH – smoothing scale varies with direction Exactly energy conserving</p> <p>Strength model generally employed: Tensor form of the Benz and Asphaug damage model</p> <p>Porosity: Strain-alpha porosity model</p>	Owen, et al. 1998; Owen 2014
iSALE-2D	Explicit Arbitrary Lagrangian Eulerian, continuum representation of materials	<p>2D geometry; finite difference solutions Allows multiple materials and rheologies</p> <p>Strength/Damage model generally employed: Pressure-dependent yield based on Collins et al. (2004), which tracks damage based on deviatoric strain</p> <p>Porosity: Epsilon-alpha porosity model (Wünnemann et al. 2006; Collins et al. 2011)</p>	Amsden et al. 1980 Wünnemann et al. 2006
RAGE	Adaptive Eulerian Grid, Continuous Adaptive Mesh Refinement, continuum representation of materials	<p>1-3D Geometry; Multidimensional simulations Radiation Adaptive Grid Eulerian Adaptive mesh and time steps Includes: Radiative transfer, heat conduction SESAME and analytical EOS available Multiple strength models available</p>	Gittings et al. 2008



		Porosity: p-alpha porosity model	
PAGOSA	Eulerian, Continuum	3D, fixed grid, Eulerian Hydrocode 2nd order accurate in time, 3rd order accurate in space Adaptive time steps Allows multiple materials per cell  Variety of strength models available, Johnson-Cook damage model usually employed SESAME and analytical EOS available  Porosity: p-alpha porosity model	Weseloh, Clancy, and Painter, 2010

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Though relevant to modeling for the DART mission, the aim of the presented study is to evaluate the results of several numerical codes against one another in a standard set of cases rather than for the actual DART impact. Basalt and aluminum were chosen as projectile and target materials for many of the cases because of the availability of extensive experimental databases and because these materials are already implemented or can be implemented readily for impact simulations. The EOS was standardized between models so as to remove that as a variable (Table 2, Table 3). Where appropriate, strength parameters for aluminum and basalt were also proscribed (Table 4). The four standard cases (summarized in Figure 1 and Table 5) were intended to isolate the effects of: 1) impact flow field modeling, 2) brittle failure and fracture effects, 3) target porosity effects, and 4) finite size target effects. These were investigated by examining specific variables of interest to the DART project, including: the momentum enhancement factor,  $\beta$ , the ejected mass, the crater size (width and depth), and the peak pressures beneath the impact point. Note that strength changes as a function of porosity were neglected in these cases. This limits the number of parameter changes between models and allows for better understanding of controlling parameters.

**Table 2.** Summary of parameters in the Mie-Grüneisen EOS for aluminum 6061

Material	R0 (initial density for Hugoniot)	T0 (initial temp)	Sound speed (Cs)	S1	Grüneisen parameter	Specific heat (cal/g*degC)
Al-6061	2.703	2.59E-2 eV	5.22 km/s	1.37	1.97	1.07E+11

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**Table 3.** Summary of parameters for the Tillotson EOS [Benz and Asphaug, 1999; Tillotson, 1962]

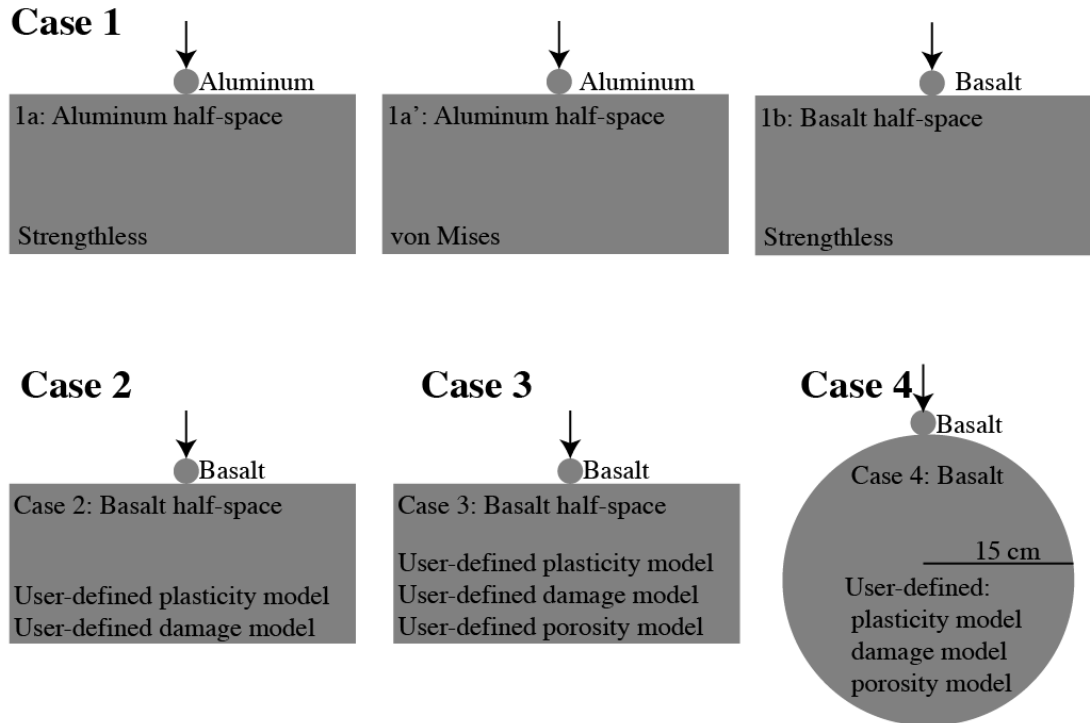
Material	$\rho_0$ (kg/m <sup>3</sup> )	A (J/m <sup>3</sup> )	B (J/m <sup>3</sup> )	E0 (J/g)	Eiv (J/g)	Eev (J/g)	a	B	alpha	$\beta$
Basalt	2700	2.60E+10	2.67E+10	4.87E+5	4.72E+3	1.82E+4	0.50	1.50	5.00	5.0 <sup>a</sup>
Aluminum	2700	7.52E+10	6.50E+10	5.00E+3	3.00E+3	1.50E+4	0.5	1.63	5	5

248 a. Tillotson parameter for lunar gabbroic anorthosite [O'Keefe and Ahrens, 1982], substituting  
 249 the basalt reference density and bulk modulus as reported by Nakamura and Fujiwara (1991)  
 250  
 251

**Table 4.** Summary of parameters prescribed for basalt and Al-6061

Basalt	Fully dense	20% porosity	45% porosity	60% porosity
Density [kg/m <sup>3</sup> ]	2800	2600	1500	1200
Quasistatic Compressive strength [MPa]	400	400	400	400
Dynamic Compressive Strength [MPa]	600	600	600	600
QS Tensile strength [MPa]	30	30	30	30
Dynamic Tensile Strength [MPa]	80	80	80	80
Toughness Mpa $\sqrt{m}$	1.6	1.6	1.6	1.6
Youngs Modulus [GPa]	70	70	70	70
Shear Modulus [GPa]	29	29	29	29
Bulk Modulus [GPa]	49	49	49	49
Coefficient of Friction	0.6	0.6	0.6	0.6
Poisson's ratio	0.25	0.25	0.25	0.25
<b>Aluminum</b>				
Al-6061, constant strength Yield Strength	275 MPa	--	--	--
Poisson's ratio	0.33	--	--	--
Porosity	0%	--	--	--

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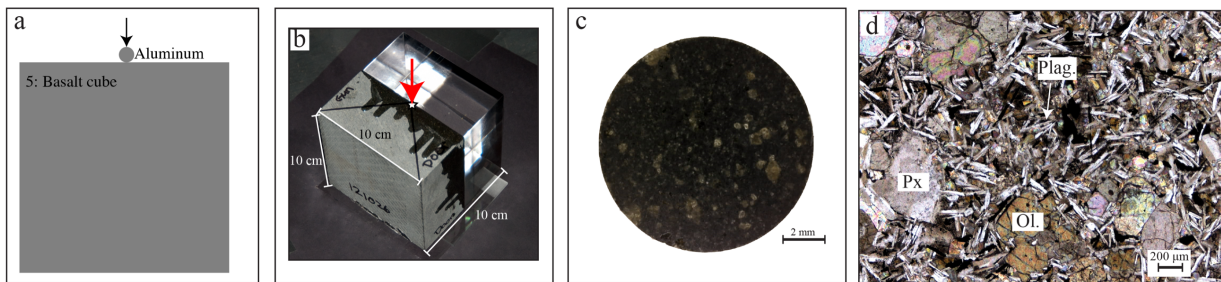
253  
254 **Figure 1.** Schematic of standard benchmarking cases sent to each team. Cases were designed as  
255 laboratory-scale simulations and to isolate specific effects. Standard materials and models were  
256 assumed across the codes.

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260 **Table 5.** Summary of the initial 4 cases compared across codes and their purpose

	Projectile	Target	Velocity	Impact Angle (deg)	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Damage model	Porosity Model	Porosity value	Intended to study	Resolution (cpr or equivalent)	Geometry
Case 1a	0.635-cm Al sphere	Al halfspace	5 km/s	90	Mie-Grüneisen Al 6061	Mie-Grüneisen Al 6061	none	none	none	none	0	Impact flow field modeling	3,5,7 (LLNL, 3D) 5,10,20,40 (LLNL, 2D)	2D, 3D
Case 1b	0.635-cm basalt sphere	basalt halfspace	5 km/s	90	Tillotson	Tillotson	none	none	none	none	0	Impact flow field modeling		2D, 3D
Case 2	0.635-cm basalt sphere	basalt halfspace	5 km/s	90	Tillotson	Tillotson	user specified/code dependent	user specified/code dependent	user specified/code dependent	none	0	Brittle failure and fracture effects	5, 10, 20	2D, 3D
Case 3	0.635-cm basalt sphere	basalt halfspace	5 km/s	90	Tillotson	Tillotson	user specified/code dependent	user specified/code dependent	user specified/code dependent	user specified/code dependent	20, 45, 60%	Target Porosity effects		2D, 3D
Case 4	0.635-cm basalt sphere	30-cm basalt sphere	5 km/s	90	Tillotson	Tillotson	user specified/code dependent	user specified/code dependent	user specified/code dependent	user specified/code dependent		Finite target size effects		2D, 3D
Constant Strength	0.625-cm Al 6061 sphere	Al 6061 halfspace	5 km/s	90	Mie-Grüneisen Al 6061	Mie-Grüneisen Al 6061	von Mises	von Mises	none	none	none	Impact flow field with simple strength model		2D, 3D

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263 A fifth case was designed to validate the numerical simulations against a hypervelocity impact  
264 experiment performed at the NASA Ames Vertical Gun Range (AVGR). This case was not  
265 simulated using every code. The experiment was a 90° impact, at 2.1 km/s, into a 10 cm x 10 cm  
266 x 10 cm block. The block was made of two parts: 1 10 cm x 10 cm x 5 cm basalt block affixed to  
267 a 10 cm x 10 cm x 10 cm polymethylmethacrylate (PMMA) block. The PMMA was chosen to  
268 match impedance with the basalt and was used as a window to examine crater growth as a function  
269 of time following impact (Figure 2A,B). Because the purpose of this case was specifically to

270 compare and validate numerical simulations against experimental results (e.g., Figure 18), the  
 271 impact geometry and velocity are not required to match the other 4 Cases. Rather, this experiment  
 272 serves as a “blind” test of the simulations accuracy because the experimental results were not  
 273 shown to the specific individuals tasked with simulating the experiment prior to running the model  
 274 and reporting the results. The simulated case modeled the impact of a 0.635-cm Pyrex sphere into  
 275 a 10-cm x 10-cm x 10-cm basalt block at 2.1 km/s, neglecting the PMMA window for simplicity.  
 276 The choice of EOS, plasticity, and damage model was left to the user. However, the basalt block  
 277 was stipulated to have the following properties: quasi-static uniaxial compressive strength = 400  
 278 MPa; dynamic uniaxial compressive strength = 600 MPa; Quasi-static tensile strength = 30 MPa;  
 279 Dynamic tensile strength = 80 MPa; Youngs modulus = 70 GPa ; density = 2800 kg/m<sup>3</sup>; and  
 280 fracture toughness = 1.6 MPa √m. These parameters were determined from the specific basalt  
 281 samples used in the experiment (Figure 2C,D).  
 282



283  
 284 **Figure 2.** Setup for the experiment for comparisons in Case 5. a) Schematic of impact geometry;  
 285 b) setup of the actual impact experiment, showing the basalt block with PMMA window. Impacts  
 286 were from the top at the center of the block, and the block was set atop two glass slides to minimize  
 287 interactions with the floor of the vacuum chamber following impact; c) small cutout showing  
 288 texture of the basalt with visible olivine phenocrysts; d) thin section of the basalt used. The basalt  
 289 was a fine-grained Columbia River flood basalt.  
 290

291 *2.1 Codes Used in This Study*

292 **2.1.1 CTH Simulations**

293 CTH is an Eulerian shock-physics code developed at Sandia National Laboratories [McGlaun  
 294 et al., 1990] that has been applied to a wide variety of high speed large deformation problems, e.g.  
 295 planetary impact cratering. It has the ability to perform multi-dimensional, multi-material  
 296 calculations for a wide range of material models and EOS. For all benchmark cases both 2D and  
 297 3D CTH simulations were performed to examine its effect on  $\beta$  as well as the crater dimensions.  
 298 All simulations were run using CTH version 12.0.

299 The amount of momentum transfer from the impact as a function of time,  $\beta(t)$ , was calculated  
 300 for each simulation. All mass in the simulation moving upward (positive y direction in 2D, positive  
 301 z direction in 3D) in the plane above the initial impact plane was assigned as “ejecta mass”. The  
 302 ejecta momentum was then calculated as,  $p_i = m_i v_i$ , where  $p_i$  is the momentum of the  $i$ th piece of  
 303 ejecta,  $m_i$  is its mass, and  $v_i$  is the ejecta velocity. The 90% percentile velocity for ejecta at a given  
 304 time step was calculated and used. To limit computational requirements, the mesh extent was  
 305 limited. All mass crossing the mesh boundary (and thus leaving the simulation) was tracked. This  
 306 lost momentum was defined as the lost mass times the 90<sup>th</sup> percentile of the ejecta velocities at a  
 307 given time step. The momentum multiplication factor,  $\beta$ , is calculated as the sum of the ejecta  
 308 momentum and lost momentum divided by the projectile momentum for all pieces of ejecta mass.

309 Impact crater dimensions were calculated using two different algorithms, “simple” and  
310 “robust”. For nonporous simulations, the depth and width of the crater were calculated with a  
311 “simple” method: The cells of the target material along the projectile velocity vector were tracked,  
312 and the minimum absolute value of the height location of any of these cells was assigned as the  
313 crater depth. Crater diameter (width) was calculated by tracking the cells along the impact plane.  
314 The minimum absolute value of the non-depth dimensions (y in 2D, x and y in 3D) corresponds to  
315 the side of the impact crater. Crater diameter was assumed to be the distance between cells along  
316 this crater profile on the plane where the projectile first contacted the target.

317 Simulations of impacts into porous targets generated numerical artifacts that disrupted the  
318 “simple” algorithm described above, and a more robust algorithm was needed. For example, in  
319 2D simulations a small upward moving jet along the centerline was seen, which resulted in an  
320 artificially shallow crater being identified using the simple algorithm described above. The  
321 “robust” algorithm is defined here: to calculate crater depth, the algorithm was modified and a  
322 scan along the dimensions of interest was performed, i.e., along the x-direction in a 2D simulation  
323 or along the x and y-direction in a 3D simulation. The minimum absolute value of the height  
324 location was recorded for each cell column in these dimensions. The global minimum of these  
325 values thus defines the crater depth. Care was taken to ensure that if small vacancies exist in the  
326 impacted material, these vacancies were not mistaken for the crater floor. Calculating crater width  
327 required a similar scan to be performed in the appropriate dimensions along the impact plane (y=0  
328 for 2D, z=0 for 3D). The width was defined as the maximum value of the vector length connecting  
329 impacted material.

330 Adaptive Mesh Refinement (AMR) [Crawford, 1999] was utilized in all simulations for  
331 computational efficiency, with refinement occurring for all projectile material and at moving  
332 interfaces. For 2D simulations, the resolution ranged from 5-20 cppr while for 3D simulations the  
333 resolution ranged from 2.5-5.5 cppr. Convergence tests were performed for Case 1a and Case 2  
334 (in 2D) and Case 1a (in 3D) to examine the effect of resolution on crater dimensions and  
335 momentum transfer. The effect of grid size on the calculation of  $\beta$  was also examined. Resolution  
336 studies determined that the calculated  $\beta$  was not dependent on the extent of the mesh so long as  
337 the ejecta mass was accurately tracked.

338

### 339 **2.1.2 CTH Parameters**

340 Two separate strength and damage models were used within CTH for these benchmarking  
341 cases: the “geo” model and the “BDL” model. The “geo” yield surface is a pressure-dependent  
342 yield surface incorporating thermal softening and density degradation. This yield behavior was  
343 coupled to a Johnson-Cook fracture (JCF) model to track damage within the material. The JCF  
344 model is a scalar damage model used to predict failure of materials [Johnson and Cook, 1985]. A  
345 damage parameter, D, ranges from 0 (pristine, undamaged material) to 1 (failed material), where  
346 D is a function of equivalent plastic strain rate, local value of plastic strain to fracture, pressure,  
347 local yield stress, temperature and loading path. Here, D is assumed to be a function of the local  
348 value of plastic strain to fracture and material heterogeneity (in the form of Weibull distributed  
349 flaws) only. Damage by extensional failure (spallation) occurs when the material undergoes  
350 stresses higher than the maximum tensile stress.

351 The second strength and damage model used in CTH benchmarking simulations was the Brittle  
352 Damage with Localized Thermal Softening (BDL) model [Crawford *et al.*, 2013; Schultz and  
353 Crawford, 2016]. This model includes a pressure-dependent yield and brittle damage model  
354 similar to that of Collins *et al.* [2004], in which the plastic strain at failure increases across the

355 brittle and ductile regimes and the yield strength of fully damaged material follows a Coulomb  
356 friction law. The BDL model also incorporates a pressure-dependent melt curve [*Senft and*  
357 *Stewart*, 2009] to compute thermal softening and a statistical crack model [*Schultz and Crawford*,  
358 2016]. The crack spacing follows a power law in strain rate, and within cracks localized  
359 temperature changes are induced by frictional shear heating and heat loss due to thermal  
360 conduction.

361 For Case 5, which differs slightly from the prescribed Cases 1-4, CTH simulations were run  
362 with the Tillotson equation of state and the BDL model with stipulated strength parameters for  
363 basalt. The Pyrex projectile was simulated using a Mie-Gruneisen equation of state and a pressure-  
364 dependent yield surfaces with parameters from Stickle and Schultz [2014] and Marsh [1980]. The  
365 parameters for the Pyrex were set to mimic the breakup behavior seen in experiments. A Johnson-  
366 Cook continuum damage model (“Johnson-Cook Fracture, [*Johson and Cook*, 1985]) was added  
367 with a strain-to-failure of 5%, a melting temperature of 2900K, a tensile strength of 1.8 GPa and a  
368 Weibull modulus of 10.

369

### 370 **2.1.3 Adaptive Smooth Particle Hydrodynamics**

371 Spheral is an open-source Adaptive Smoothed Particle Hydrodynamics (ASPH) code [*Owen et al.*,  
372 1998; *Owen*, 2010], which has been used extensively for small-body cratering studies [*Owen et*  
373 *al.*, 2014; *Owen et al.*, 2015; *Bruck Syal et al.*, 2016a; *Bruck Syal et al.*, 2016b]. Meshless  
374 hydrodynamics methods such as ASPH allow for the momentum carried in crater ejecta to be  
375 calculated in a relatively straightforward manner as the ejecta particles are automatically tracked  
376 as they move. Spheral differs from most standard implementations of SPH in that the smoothing  
377 scale between particles can vary with direction, which allows for more realistic treatment of  
378 strongly anisotropic strain fields; it is also exactly energy conserving [*Owen et al.*, 2014].

379 For this study, most Spheral simulations were carried out in a fully 3D geometry, so that damage  
380 propagation in the basalt targets could be more accurately tracked. Some axisymmetric (2D)  
381 simulation for Case 1 (aluminum target, without damage) were carried out to assess differences  
382 between 2D and 3D geometries. Convergence tests were performed for both crater size and  
383 momentum transfer in 2D and 3D simulations. Note that Spheral resolution is described by “nrI,”  
384 the number of ASPH particles per impactor radius (similar to the cells-per-projectile-radius or  
385 “cpr” metric used by meshed codes).

386 Half-space targets (Cases 1, 2, and 3) were modeled using high resolution in the area of crater  
387 formation (5-7 particles-per-projectile-radius, out to a radius of 3 cm), with resolution gradually  
388 becoming coarser towards the edge of the domain (at a radius of 12 cm). These limits were chosen  
389 through an iterative process to determine when simulation results were not affected by interactions  
390 at the edge of the target, and through comparisons with constant-resolution targets. Similarly, high  
391 resolution (5 particles-per-projectile-radius) was used near the crater in Case 4 (30-cm spherical  
392 target), with resolution gradually coarsening beyond 5 cm in radius from the impact point. Uniform  
393 resolution (5 particles-per-projectile-radius) was used in Case 5 (10-cm cube target).

394 Tillotson EOS parameters were used for all aluminum and basalt materials (Table 3). For all  
395 cases, summaries of parameters used can be seen in Appendix A. For the Pyrex impactor in Case  
396 5, Mie-Gruneisen coefficients from *Stickle & Schultz* (2012) were chosen to represent the Pyrex.  
397 Aluminum strength, when used, was represented using the von Mises criterion, using a constant  
398 yield strength of  $Y_0 = 275$  MPa and a shear modulus of  $G = 26.5$  GPa. Basalt targets also used  
399 von Mises strength, with  $Y_0 = 1$  GPa and  $G = 29$  GPa. This strength model was coupled to a tensor  
400 generalization of the Benz-Asphaug implementation of Grady-Kipp damage for SPH codes [*Benz*

401 *and Asphaug, 1994*]. The damage model used a version that is compatible with particles of varying  
402 resolution and applied the “pseudo-plastic” strain algorithm, with  $k = 5e24 \text{ cm}^{-3}$  and  $m = 9.0$  for  
403 the Weibull constants. Porosity was modeled using the  $\epsilon$ - $\alpha$  strain-based model [*Collins et al.*,  
404 2011], with values of  $\epsilon\epsilon = 0.0$ ,  $\epsilon\chi = -0.4$ , and  $\kappa = 0.8$ . Case 3 (half-space target) used porosities of  
405  $\phi = 0.2$  and  $0.4$  and Case 4 (sphere target) used  $\phi = 0.2$ . For Case 5, which aimed to simulate a real  
406 basalt target used in an impact experiment, we assumed that some natural porosity would have  
407 been present in the sample ( $\sim 7\%$ ), and used a reference density of  $3.01 \text{ g/cc}$  so that the bulk density  
408 of the block was  $2.8 \text{ g/cc}$  (the measured value).

409

#### 410 **2.1.4 iSALE simulations**

411 The iSALE-2D shock physics code [*Wünnemann et al.*, 2006] is based on the SALE hydrocode  
412 solution algorithm [*Amsden et al.*, 1980]. SALE was modified to include an elasto-plastic  
413 constitutive model, fragmentation models, various EOS, and multiple materials in order to simulate  
414 hypervelocity impact processes in solid materials [*Melosh et al.*, 1992; *Ivanov et al.*, 1997]. More  
415 recent improvements include a modified strength model [*Collins et al.* 2004] and a porosity  
416 compaction model [*Wünnemann et al.*, 2006; *Collins et al.*, 2011].

417 iSALE was used to simulate Cases 1-4. The Tillotson EOS was used in all cases, the “ROCK”  
418 strength model [*Collins et al.*, 2004] was used for basalt in all cases requiring strength, while the  
419 Johnson-cook strength model [*Johnson and Cook*, 1983] was used for aluminum. The “Collins”  
420 damage model [*Collins et al.*, 2004] was used where a damage model was present, and has shown  
421 accurate results for comparisons with laboratory experiments on competent rocks in previous  
422 studies [*Güldemeister et al.* 2015, 2017, *Winkler et al.* 2018]. For cases requiring porosity, the  $\epsilon$ -  
423  $\alpha$  [*Wünnemann et al.*, 2006; *Collins et al.*, 2011] was used. A convergence study was performed  
424 for *Cases 1a' and 2*, with resolutions ranging from 5-60 cppr.

425 The mass and velocity of ejected material is analysed with the help of Lagrangian tracer  
426 particles that are initially distributed uniformly across the computational domain, in the centre of  
427 each computational cell. These tracers follow the velocity field of the material flow in the Eulerian  
428 grid. Upon ejection, which is defined as the moment when the tracer reaches an altitude of one  
429 projectile radius, the speed and angle of ejection and the radial launch position is recorded. The  
430 upward directed momentum represented by each ejected tracer particle is summed and normalised  
431 by the impactor momentum to derive a  $\beta$  value for the simulation. A significant benefit of this  
432 approach is that once the tracer particle has crossed the ejection altitude the material that it  
433 represents no-longer needs to be tracked. This ensures accurate recording of even the fastest ejecta  
434 and negates the need to record momentum lost from the computational domain. Studies of the  
435 effects of target properties on ejecta characteristics that include a more detailed description and a  
436 validation of this approach were recently published [*Luther et al.* 2018, *Raducan et al.*, submitted].  
437 This approach has successfully reproduced the morphometry of ejecta deposits formed in  
438 laboratory experiments [*Wünnemann et al.* 2016] and surrounding lunar craters [*Zhu et al.*, 2015],  
439 and was used to quantify momentum enhancement for strength-dominated target materials in low-  
440 gravity environments applicable to the DART mission scenario [*Raducan et al.*, submitted]. In  
441 *Case 1a'*,  $\beta$  was calculated from the cell momenta (a similar method to that employed in CTH)  
442 instead of the tracer method to reduce intercode variability.

443

#### 444 **2.1.5 Radiation Adaptive Grid Eulerian (RAGE)**

445 RAGE is a multi-dimensional, multi-material Eulerian shock physics code developed by Los  
446 Alamos National Laboratories (LANL) [*Byrne et al.*, 1992; *Gittings et al.*, 2008]. The code

447 includes adaptive time steps, adaptive mesh refinement, a  $p$ - $\alpha$  porosity model, a variety of strength  
448 models, and both SESAME [Lyon and Johnson, 1992] and analytical EOS capabilities. RAGE was  
449 used to simulate Case 1a (strengthless models) for impacts in both aluminum and basalt, and Case  
450 1b for impacts into aluminum with a Steinburg-Guinan plasticity model [Steinberg *et al.*, 1980].  
451 A resolution test was performed for each case, with the finest resolution of 0.031 cm (20 cppr).  
452 Since RAGE is an AMR code, the resolution refers to the finest allowed resolution. The code  
453 automatically refines or coarsens cells according to the gradients of the state variables in  
454 neighboring cells, so that the mesh is refined to a high resolution in the presence of shocks and  
455 coarsened in areas where there is little motion.

456 The simulations were carried out on a 2-D cylindrical axi-symmetric grid, with the impact on  
457 the axis of symmetry. Eulerian codes cannot support empty mesh cells, therefore a background  
458 atmosphere is included in all cases. A 1 bar SESAME air EOS is used as a background material  
459 for models of laboratory experiments in air, and a 100 microbar monatomic ideal gas is used for  
460 models of impacts in vacuum.

### 461 462 **2.1.6 PAGOSA**

463 PAGOSA [Weseloh *et al.*, 2010] is a massively parallel hydrocode developed by LANL to simulate  
464 multi-dimensional dynamic behavior of solid materials subjected to high-strain rates, like those  
465 produced by hypervelocity impacts. PAGOSA is an Eulerian finite-difference code, has adaptive  
466 time steps, a  $p$ - $\alpha$  porosity model, multiple strength models, and both SESAME and analytical  
467 EOS capabilities. It uses an up-stream weighted, monotonicity-preserving advection scheme that  
468 conserves momentum and internal energy. PAGOSA uses a fixed grid mesh throughout the entire  
469 simulation. Cell size may be varied spatially so that some regions of the mesh have a higher  
470 resolution than others, but the mesh cannot change over the course of the calculation.  
471 Homogeneous-sized meshes are used throughout this work, with all cells in the mesh at the  
472 reported resolution of the specified model. A resolution test was performed for each case, with the  
473 finest resolution of 0.031 cm (20 cppr). PAGOSA was used to simulate Case 1a strengthless  
474 models and Case 1b impacts into aluminum with a Steinburg-Guinan plasticity model [Steinberg  
475 *et al.*, 1980]. The models were run as 2D axisymmetric models for efficiency.

476 For both RAGE and PAGOSA simulation, the momentum of all material moving in the  
477 positive  $y$ -direction (up in the images, opposite the impact velocity direction) above the original  
478 target surface was tracked and added to the original projectile momentum. This quantity was then  
479 divided by the original projectile momentum to determine the momentum enhancement factor,  $\beta$ .

## 480 481 **3. Benchmarking Results**

482 Benchmarking impact codes requires identification of standard cases that are repeatable across  
483 different codes that allow a comparison of the performance in accuracy, speed, and reliability. This  
484 testing requires detailed comparison of simulation results and characteristic quantities across the  
485 codes. Here, we compare crater growth and dimensions, peak pressures in the target following  
486 impact, and the momentum enhancement factor,  $\beta$ . We present results from the time of impact  
487 until the crater size and  $\beta$  have stabilized. Not every case includes results from each numerical  
488 method.

### 489 490 *3.1 Case 1 – 1/4" sphere into half-space (strengthless)*

491 The first benchmarking case was designed to identify how codes behave with respect to one  
492 another using the simplest model: a strengthless target. This setup requires no additional material



493 constitutive behavior outside the equation of state. This case was initially broken into two parts:  
 494 Case 1a, an aluminum sphere impacting into an aluminum target, and Case 1b, a basalt sphere  
 495 impacting into a basalt target. All material in Case 1a and 1b was simulated using only an EOS  
 496 with no additional plasticity model. This separation was intended to provide a better understanding  
 497 of the effects of differing EOS on the  $\beta$  calculation. Following initial simulation tests, a third  
 498 variant was added to Case 1, called Case 1a' here. This variant included simulations using constant  
 499 strength (represented using a von Mises plasticity model) for the aluminum block. This simple  
 500 strength approximation is available in most widely used codes and thus represented an initial  
 501 baseline to better understanding the natural variability found between codes when strength is  
 502 included. Because it is implemented widely, this provided a more direct comparison between codes  
 503 than later cases which include significantly more variation in plasticity and damage model  
 504 implementation and choices between codes. These results are summarized below.

505 Figure 3 shows the results from Case 1a and 1b using 5 different numerical codes. Spheral,  
 506 RAGE and PAGOSA performed a convergence test for this case. More detail regarding the results  
 507 of the RAGE and PAGOSA convergence study are summarized in *Heberling et al.* [2017]. For  
 508 both Spheral and PAGOSA simulations, predicted  $\beta$  decreases with increasing resolution. This  
 509 trend is opposite for RAGE simulations, where  $\beta$  increases as resolution increases.

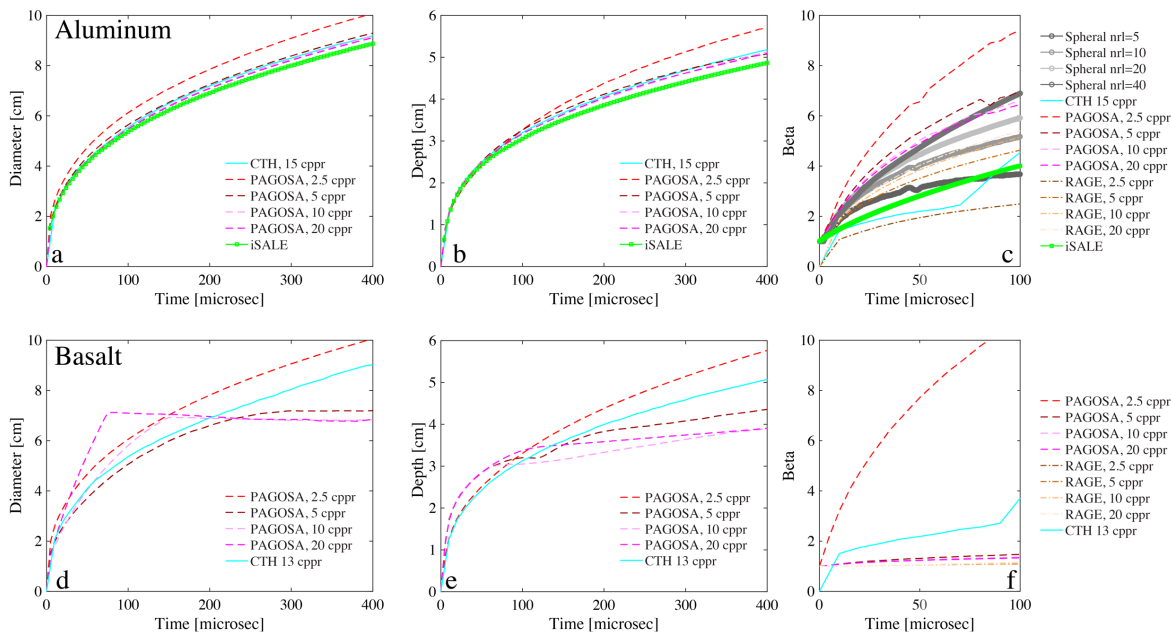
510 Crater size shows the least variation between codes. Note that because the simulations do not  
 511 include material strength, there is nothing to stop the crater growth, and the values for depth and  
 512 diameter do not asymptote. This is expected, so a common stop time was prescribed for these  
 513 simulations. Here, we chose 400  $\mu$ sec, as this time would be well beyond the transient crater  
 514 formation time for a typical laboratory experiment. There is a larger variation in the reported values  
 515 for momentum enhancement factor,  $\beta$ , thus it is shown until 100  $\mu$ sec for clarity. A more complete  
 516 summary of values from each code is shown in Appendix B, however a few noted results are  
 517 summarized here in Table 6. At 100  $\mu$ sec following impact, there is a 3-4% difference in crater  
 518 depth and diameter between codes, while the percent difference between the minimum and  
 519 maximum  $\beta$  is 37% for comparable resolution. At 400  $\mu$ sec this difference is 3.5%, 6% and 15%  
 520 difference in depth, diameter, and  $\beta$  predictions. For comparable resolutions, 2D CTH simulations  
 521 predict the largest crater and  $\beta$  values at 400  $\mu$ sec. The large scatter between the CTH and  
 522 PAGOSA simulations for impacts into a strengthless basalt target is likely due to the fact that the  
 523 CTH simulations modeled a target with 0% porosity while the PAGOSA and RAGE simulations  
 524 modeled a basalt target with 50% porosity. Higher porosity will result in deeper, narrower craters,  
 525 and lower  $\beta$ . This is generally what is seen in all but the lowest resolution PAGOSA models.  
 526 However, 2.5 cppr is such a coarse resolution that the results are not likely to be accurate. From  
 527 the CTH simulations, we see that there is not a large difference between predicted crater depth,  
 528 diameter and  $\beta$  values due to the EOS differences between aluminum and basalt.

529  
 530 **Table 6.** Summary of crater size and  $\beta$  for strengthless aluminum targets (Case 1a) at 100 and 400  
 531  $\mu$ sec following impact for simulations with comparable resolution. When a given result was not  
 532 supplied by specific modelers, it is marked as “not provided” in the table. Gridded codes resolution  
 533 is reported in “cells per projectile radius” (cppr), while the resolution for the ASPH code is reported  
 534 in “nrI”, which refers to the number of ASPH particles per impactor (projectile) radius. A full  
 535 summary at all resolutions can be seen in Appendix B.

Model	Resolution	Case	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
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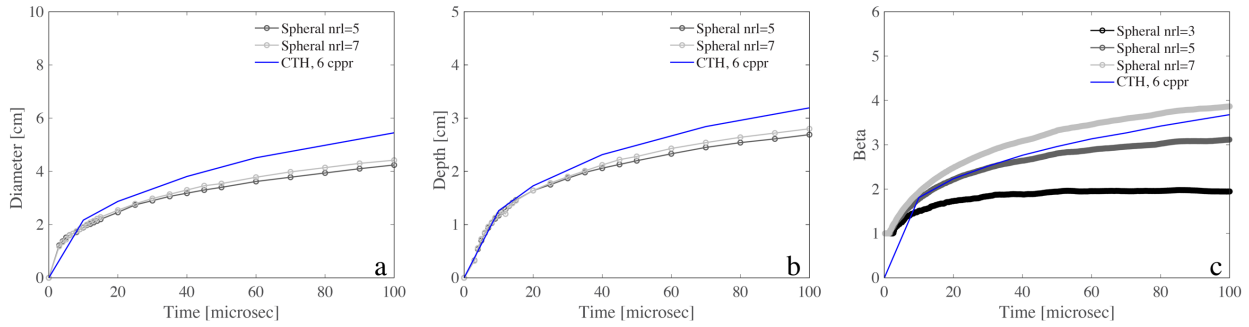
iSALE	40 cppr	1a	100	3.05	5.37	4.02
CTH (2D)	20 cppr	1a	100	3.20	5.54	4.54
RAGE	20 cppr	1a	100	not provided	not provided	5.40
PAGOSA	20 cppr	1a	100	3.17	5.47	6.45
Spheral (2D)	nrI = 20	1a	100	not provided	not provided	5.92
iSALE	40 cppr	1a	400	4.87	8.87	8.68
CTH (2D)	20 cppr	1a	400	5.18	9.19	10.22
PAGOSA	20 cppr	1a	400	5.10	9.12	10.16
RAGE	20 cppr	1a	400	5.2	8.4	9.14

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**Figure 3.** Summary of impacts into strengthless aluminum (a-c) and basalt (d-f) targets. All impacts are in 2D geometry for a 90° impact at 5 km/s. Model parameters are summarized in Tables in Appendix A. Note that because the simulations do not include material strength, the crater sizes and  $\beta$  continue to grow. a) crater diameter, in centimeters, as a function of time for 1/4" strengthless aluminum sphere impacting into a strengthless aluminum half-space; b) crater depth, in centimeters, as a function of time for 1/4" strengthless aluminum sphere impacting into a strengthless aluminum half-space; d)  $\beta$  as a function of time for 1/4" strengthless aluminum sphere impacting into a strengthless aluminum half-space; d) crater diameter as a function of time for 1/4" strengthless basalt sphere impacting into a strengthless basalt half-space; e) crater depth as a function of time for 1/4" strengthless basalt sphere impacting into a strengthless basalt half-space; f)  $\beta$  as a function of time for 1/4" strengthless basalt sphere impacting into a strengthless basalt half-space.



553  
554 **Figure 4.** Comparison of 3D Spheral and CTH simulations of impacts into strengthless aluminum  
555 targets. All impacts are at  $90^\circ$  at 5 km/s. Model parameters are summarized in Appendix A. Note  
556 that because the simulations do not include material strength, the crater sizes and  $\beta$  continue to  
557 grow. a) crater diameter, b) crater depth, c)  $\beta$ .  
558

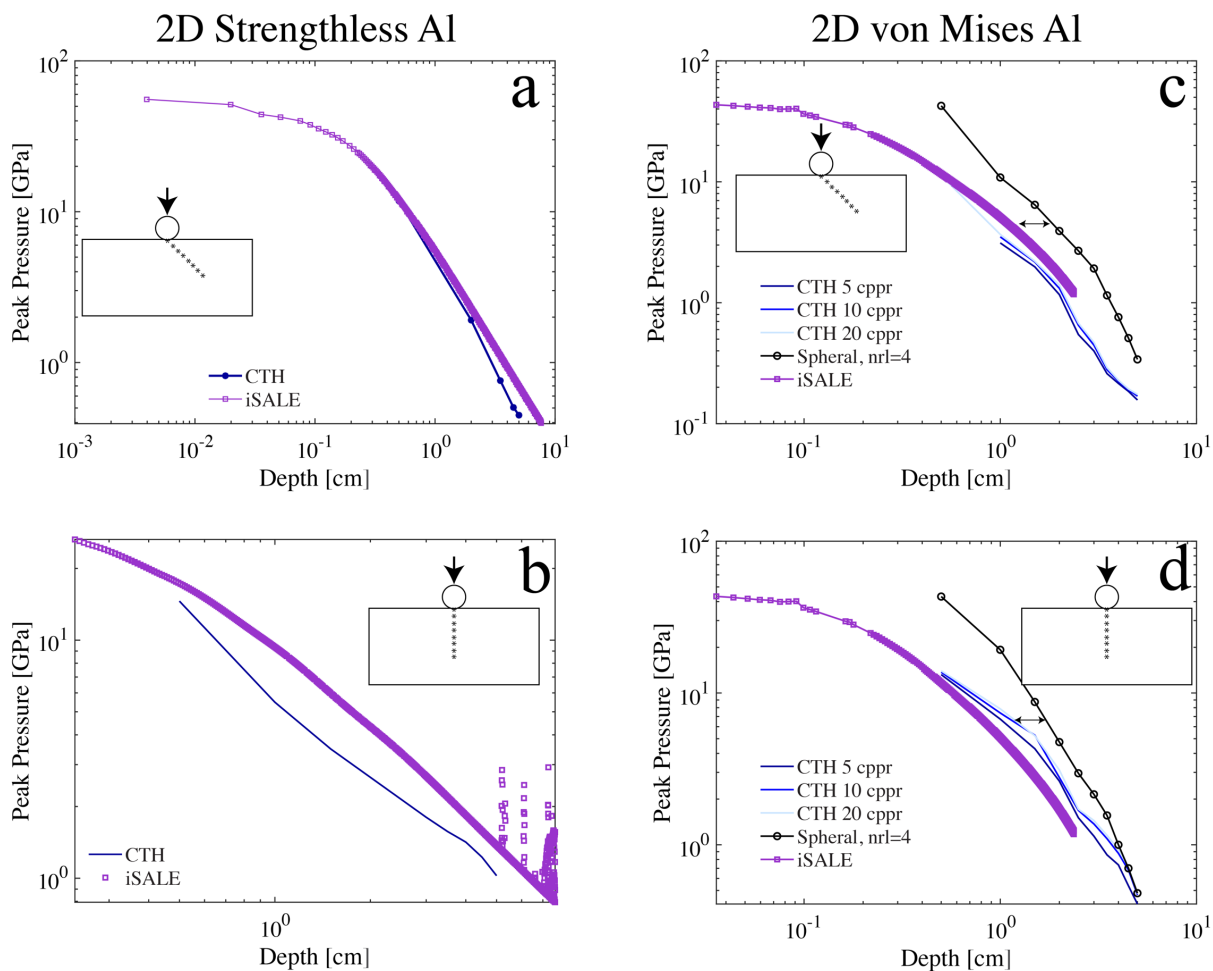
559 **Table 7.** Summary of crater size and  $\beta$  at 100 and 400  $\mu\text{sec}$  following impact for simulations with  
560 comparable resolution. When a given result was not supplied by specific modelers, it is marked as  
561 “not provided” in the table. A full summary at all resolutions can be seen in Appendix B.  
562

Model	Resolution	Case	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (3D)	6 cppr	1a	100	3.19	5.45	3.68
Spheral (3D)	nrI = 3	1a	100	not provided	not provided	1.95
Spheral (3D)	nrI = 5	1a	100	2.69	4.24	3.12
Spheral (3D)	nrI = 7	1a	100	2.80	4.42	3.87

563  
564 Three-dimensional calculations of Case 1a were also run using CTH and Spheral, and the results  
565 are shown in Figure 4 and summarized in Table 7 and in Appendix B. An additional convergence  
566 study was performed using the Spheral code in 3D.  $\beta$  values converge at slightly finer resolution  
567 (20 particles-per-projectile-radius) but converge similarly for 2D and 3D. Crater depths and  
568 diameters did not significantly differ between 2D and 3D for the aluminum targets, when run with  
569 or without von Mises (constant) strength; values for both were found to be converged at a  
570 resolution near 5 particles-per-projectile-radius. For simulations in 3D and at comparable  
571 resolution (5 cppr for CTH and nrI=5 for Spheral), CTH consistently predicted larger craters, with  
572 a 3% difference in crater diameter and 15% difference in crater depth at 100  $\mu\text{sec}$  following impact.  
573 There is a 15% difference in prediction of  $\beta$  as well.  
574

575 Another parameter that is commonly analyzed following impact is the peak pressures within the  
576 target. Here, peak pressure along a line vertically below the target as well as at depth along a  $45^\circ$   
577 slope was documented for each simulation (Figure 5). This case is similar to what was modeled in  
578 the initial benchmarking study by *Pierazzo et al.* [2008] (an impact into a strengthless aluminum  
579 target, though here the impactor is much smaller). For a 5 km/s impact, *Pierazzo et al.* [2008]

580 reported a 15% difference in slope between codes for the pressure decay region. Here, the  
 581 difference in slope of the pressure-decay region is dependent on where the peak pressures were  
 582 measured. For a line at a 45° angle radially from the impact point, the two codes predict peak  
 583 pressures within 5% of one another (Table 8, 9). However, when the peak pressure is measured  
 584 directly below the impact point, which is the generally reported direction for pressure decay  
 585 estimates in vertical impact simulations, there is a much greater difference in slopes (~40%). These  
 586 differences may be due to a number of things, including internal numerics of the codes themselves,  
 587 noise from boundary effects along the center-line of 2D simulations, as well as input parameters  
 588 chosen for each simulation. Though both codes show convergence, one obvious choice may be the  
 589 resolution of the simulations: the iSALE simulation was run at 40 cppr while CTH was run at 20  
 590 cppr. Another may be the choice of EOS parameters. Here, iSALE used the EOS for Al-1100,  
 591 while the CTH simulations used the parameters proscribed in Table 3, which may differ slightly  
 592 and affect the simulation results at early times or very near the surface (when pressures are high).  
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 596 **Figure 5.** Pressure as a function of depth for impacts into strengthless aluminum (left) and  
 597 aluminum with a constant strength (right) for simulations using CTH, iSALE, and Spheral. The  
 598 offset in the Spheral simulation is likely due to difficulty of defining stationary Eulerian tracer  
 599 points in a meshless code, which is a relatively new capability in Spheral.  
 600

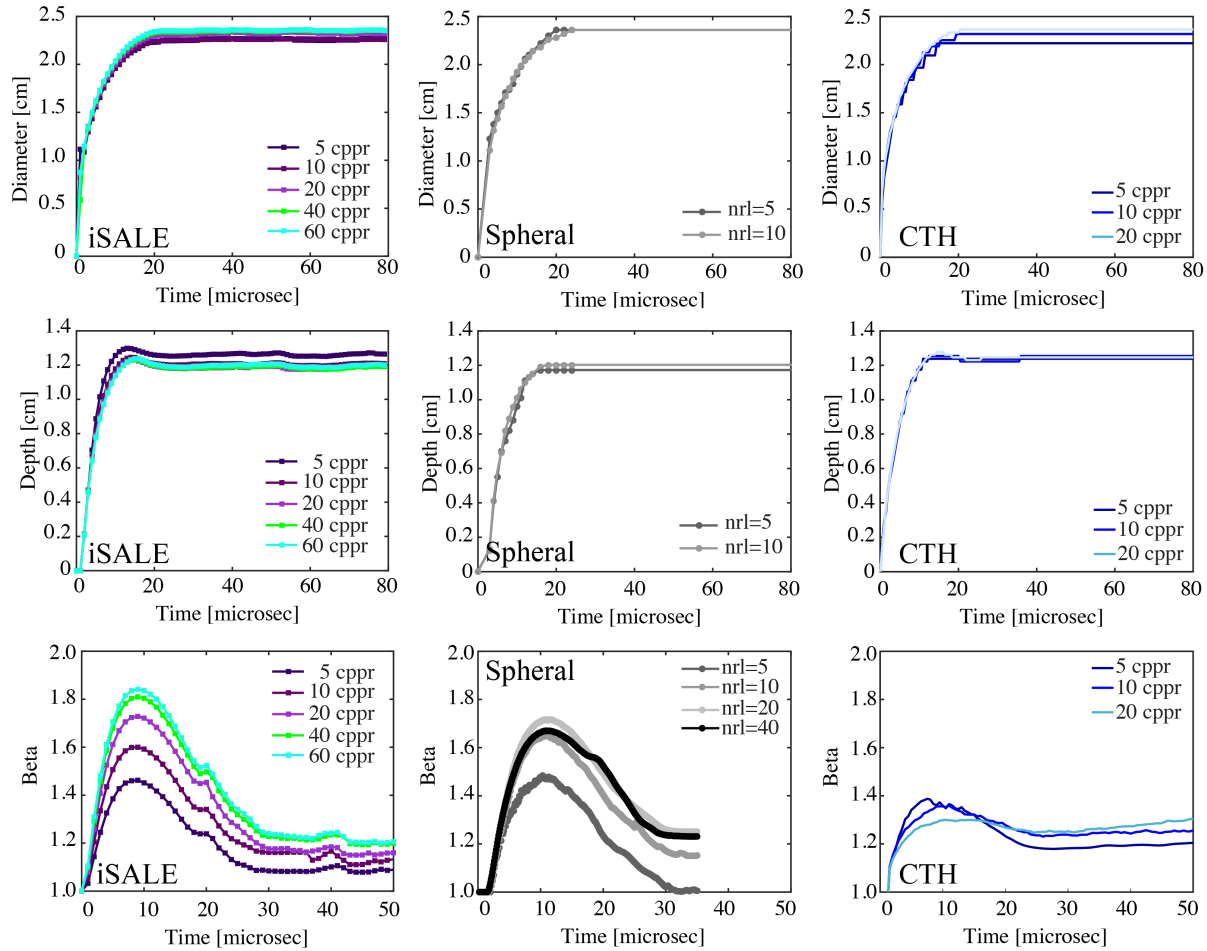
601  
 602 **Table 8.** Summary of peak pressure with depth for CTH, Spheral, and iSALE models of impacts  
 603 into a strengthless aluminum block. “diagonal” refers to tracers along a 45-deg diagonal from the  
 604 impact point, while “vertical” refers to a vertical line directly below the impact point  
 605

<b>Case 1a Strengthless</b>		Peak Pressure [GPa]	
<b>diagonal</b>	<i>Depth [cm]</i>	CTH	<i>iSALE</i>
	0.5	11.80	11.87
	2	1.91	2.23
	3.5	0.76	1.10
	4.5	0.50	0.80
	5	0.45	0.69
		Peak Pressure [GPa]	
<b>vertical</b>	<i>depth [cm]</i>	<i>CTH</i>	<i>iSALE</i>
	0.5	14.58	17.22
	1	5.49	9.32
	1.5	3.49	5.96
	3	1.80	2.68
	3.5	1.57	2.19
	4	1.42	1.84
	4.5	1.23	1.58
	5	1.02	1.37

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 607 **Table 9.** Slope of the pressure decay region for simulations of strengthless material

	<b>Slope iSALE</b>	<b>slope CTH</b>	<b>% difference</b>
diagonal	-0.52	-0.49	5.34%
vertical	-1.99	-1.12	43.84%

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 610 *3.2 Case 1a': 1/4" Sphere into Constant Strength Aluminum half-space*



611 **Figure 6.** Summary of results of a convergence study for the iSALE-2D (left), Spheral (middle),  
 612 and CTH (right) codes for an impact of a 1/4" aluminum projectile into an aluminum target that is  
 613 modeled as having constant strength. Panels show crater diameter(top), crater depth (middle) and  
 614  $\beta$  (bottom) for all three codes as a function of time and resolution. A comparison for the highest  
 615 resolution simulations can be seen in Figure 7.

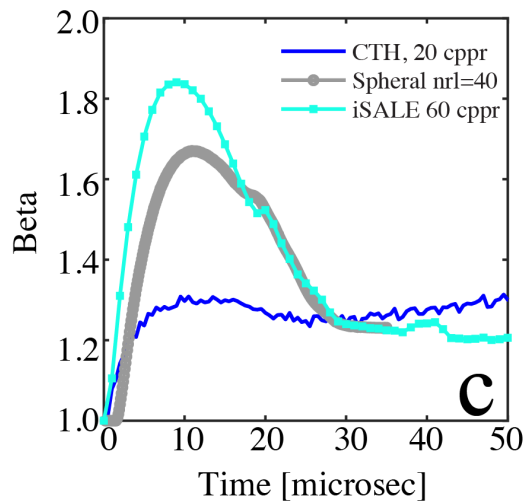
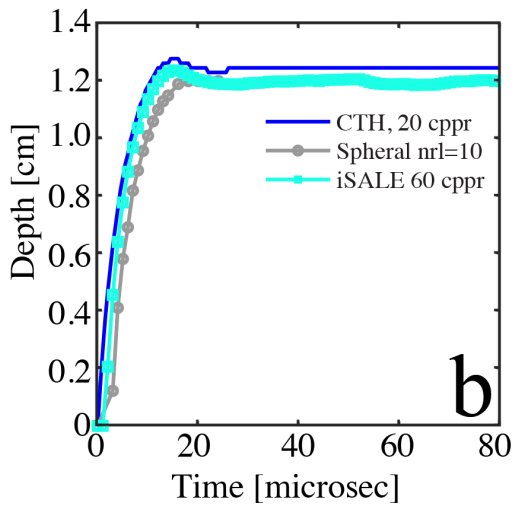
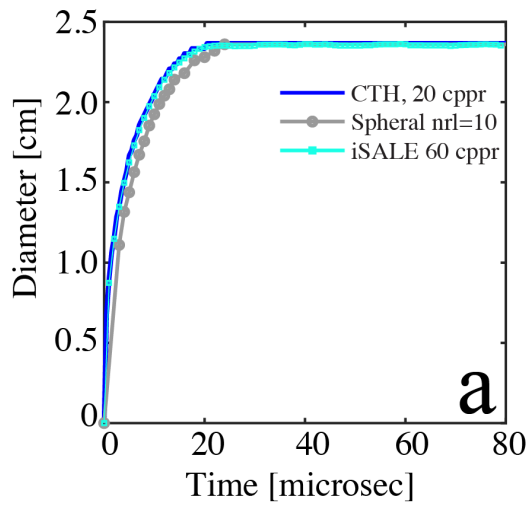
617  
 618 A modified *Case1a* in which a simple constant-strength (von Mises) strength model was employed  
 619 was also run using most of the models (*Case 1a'*). This case was performed specifically to  
 620 investigate intercode variability in strength model implementation and resolution dependence. In  
 621 order to minimize intercode differences resulting from human analysis,  $\beta$  as a function of time was  
 622 calculated from iSALE simulation results in a similar manner to CTH results, rather than using  
 623 tracer particle data. The instantaneous upward momentum of all material in the mesh above the  
 624 preimpact surface was integrated and the momentum of any material leaving the mesh through the  
 625 top boundary was accounted for. Crater size and momentum enhancement as a function of time  
 626 were compared for each simulation. Results are shown in Figure 6, Figure 7, and in Table 11 and  
 627 Table 12.

628 In this particular impact scenario, a significant portion of the uplifted crater rim acquires  
 629 substantial upward momentum during cratering, before being decelerated to rest by the target's  
 630 strength as crater growth is arrested. This acceleration and deceleration implies that the upward  
 631 momentum ( $\beta$ ) of material above the surface first increases to a maximum, before decreasing

632 asymptotically to the residual, ejected momentum. Figure 6 shows results of convergence studies  
633 performed using the iSALE-2D code, CTH and Spheral. Note that for crater size, values converge  
634 at a spatial resolution of approximately 10-20 cppr; however, convergence of the momentum  
635 enhancement factor requires higher spatial resolution of around 20-40 cppr, depending on the code  
636 used. This resolution sensitivity may be specific to this particular impact scenario, because the  
637 strength values chosen for this set of simulations resulted in a low cratering efficiency and high-  
638 speed ejecta, which often requires high resolution to track accurately. If the resolution of the  
639 simulation is too low, the high-speed ejecta is not well resolved and hence the ejected momentum  
640 is underestimated.

641 The von Mises strength model is simple and widely implemented across different codes  
642 allowing for informative intermodel comparison. The values to be used in these simulations were  
643 prescribed to the modelers (Table 5). Figure 7 shows results for simulations using CTH, iSALE-  
644 2D, and Spheral. The highest resolution from Figure 6 for each code was plotted as a comparison.  
645 The inter-code variability is low. Crater size predictions are within 5% of one another, with the  
646 greatest difference between CTH and iSALE-2D crater depth predictions (5%). The  $\beta$  value  
647 predictions vary more widely at 17% difference between the different codes (Table 10).  
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649 For *Case 1a'*, three-dimensional simulations were also considered: CTH simulations were run at  
650 5 cppr and Spheral simulations were also run at a variety of resolutions in 3D. In both cases, these  
651 simulations predicted lower values for  $\beta$  than the equivalent simulations in 2D, though crater sizes  
652 are similar.  
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**Figure 7.** Comparisons of converged results between 2D simulations from CTH, iSALE-2D and Spheral for Case 1a'. a) Crater diameter, b) depth, and c)  $\beta$  for impacts into an aluminum block with constant strength. All models are in 2D.



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**Table 10.** Results at end of simulation for CTH, iSALE and Spheral simulations simulating an impact into aluminum with constant strength. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (2D)	20 cppr	1a'	von Mises	100	1.25	2.37	1.49
iSALE (cell)	60 cppr	1a'	von Mises	80	1.19	2.36	1.41
Spheral (2D)	nrI=10	1a'	Von Mises	35	1.2	2.36	Not provided
Spheral (2D)	nrI=20	1a'	von Mises	35	not provided	not provided	1.25
Spheral (2D)	nrI=40	1a'	von Mises	35	not provided	not provided	1.23

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**Table 11.** Summary of peak pressure with depth for CTH, Spheral, and iSALE models of impacts into a constant strength aluminum block. “diagonal” refers to tracers along a 45-deg diagonal from the impact point, while “vertical” refers to a vertical line directly below the impact point.

Case 1a von Mises		Peak Pressure [Gpa]				
diagonal	depth [cm]	CTH 5 cppr	CTH 10 cppr	CTH 20 cppr	Spheral nrI=4	iSALE
	0.50	9.18	11.30	11.27	42.49	11.67
	1.00	3.12	3.50	3.67	10.86	5.02
	1.50	1.98	2.17	2.20	6.45	2.81
	2.00	1.17	1.32	1.40	3.92	1.69
	2.50	0.55	0.65	0.68	2.69	1.70
	3.00	0.40	0.45	0.47	1.92	1.37
	3.50	0.26	0.28	0.29	1.15	1.10
	4.00	0.22	0.22	0.23	0.76	0.93
	4.50	0.19	0.19	0.19	0.51	0.80
	5.00	0.16	0.17	0.17	0.34	0.69
		Peak Pressure [Gpa]				
vertical	depth [cm]	CTH 5 cppr	CTH 10 cppr	CTH 20 cppr	Spheral nrI=4	iSALE
	0.00	0.00	0.00	26.50		
	0.50	13.22	13.71	14.00	43.19	16.84
	1.00	6.73	7.38	7.86	19.26	9.07
	1.50	4.29	5.27	5.23	8.73	5.68

	2.00	2.63	2.77	3.11	4.75	4.00
	2.50	1.51	1.69	1.72	2.96	1.81 (at 2.4)
	3.00	1.14	1.37	1.45	2.15	--
	3.50	0.86	1.10	1.15	1.56	--
	4.00	0.74	0.88	0.93	1.00	--
	4.50	0.54	0.68	0.71	0.70	--
	5.00	0.41	0.47	0.48	0.48	--

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**Table 12.** Slope of the pressure decay region for impacts into a constant strength aluminum block

	<b>Slope iSALE</b>	<b>Slope CTH 5 cppr</b>	<b>Slope CTH 10 cppr</b>	<b>Slope CTH 20 cppr</b>	<b>Slope Spherical</b>
diagonal	-1.08	-2.00	-2.47	-2.46	-9.37
vertical	-7.91	-2.85	-2.94	-3.01	-9.49

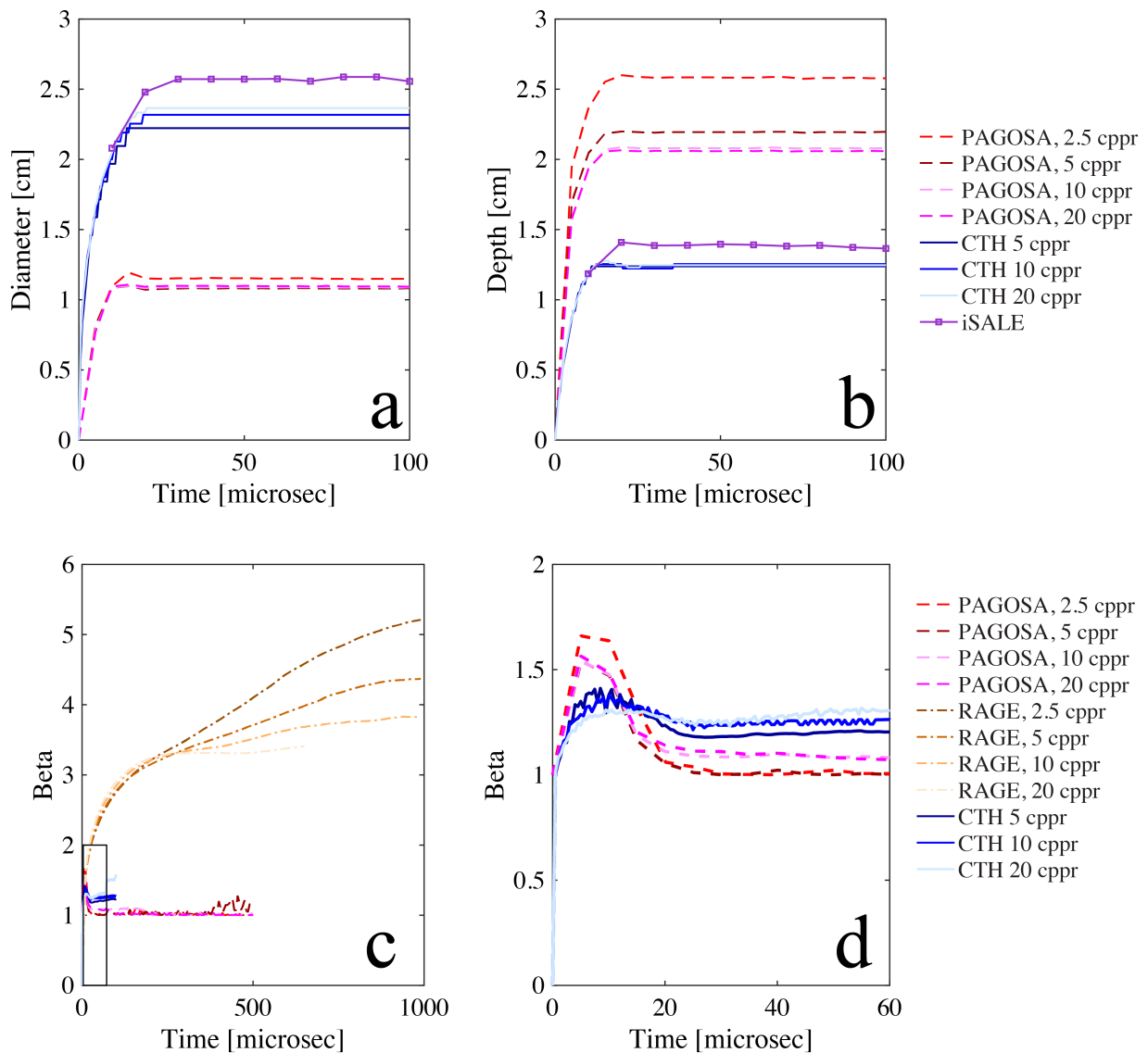
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Peak pressure values were also calculated at depth below the impact point for simulations of impact into constant strength aluminum using results from CTH, iSALE, and Spherical (Figure 5, Table 11, Table 12). Pressures were calculated directly beneath the impact point and along a radial at 45° below the impact point. The overall difference between the pressure values is not high, though the slope of the pressure-decay region in Spherical is significantly higher than in the other two codes. Both iSALE and Spherical predict high-slope pressure decay regions for a vertical line directly beneath the impact point. The pressure-decay slope increases slightly with resolution for CTH simulations.

### 3.3 Case 1a modified – other strength models

Additional simulations for impacts into an aluminum block with other strength models were also performed by most of the codes. These results are shown in Figure 8. Note here that iSALE used a Johnson-Cook [Johnson and Cook, 1983] plasticity model while PAGOSA and RAGE used a Steinberg-Guinan plasticity model [Steinburg et al., 1980] and CTH a von Mises model. At the pressures generated in a 5 km/s impact, these material behaviors are similar, though not identical. CTH, RAGE, and PAGOSA also simulated this case at multiple resolutions. Here, all parameters of interest appear to converge around 20 cppr resolution. There is significant variation in both crater size and predicted  $\beta$  between the codes, with a total variation of 40%, 57% and 65% for crater depth, diameter, and  $\beta$ , respectively. The large range in  $\beta$  is driven by the large values predicted by the RAGE code (Table 13 and Figure 8). Note that CTH and iSALE predict the closest values to one another (within 8%); iSALE consistently predicts a larger crater. Interestingly, though the predicted crater size is different between CTH and PAGOSA (Figure 8 a,b), the predicted  $\beta$  values are much more similar (30% difference).

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**Figure 8.** Impacts of a 1/4" aluminum projectile into an aluminum block at 5 km/s. a) crater diameter as a function of time, b) crater depth as a function of time, c)  $\beta$  as a function of time, d) zoom of early-times of c. Region shown in (d) is denoted by a black box in panel c.

**Table 13.** Summary of crater size and predicted  $\beta$  at 100 usec after impact. When a given result was not supplied by specific modelers, it is marked as "not provided" in the table.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
iSALE	40 cppr	1a	Johnson-Cook	100	1.37	2.56	not provided
PAGOSA	20 cppr	1a	Steinburg-Guinan	100	2.06	1.09	1.03

RAGE	20 cppr	1a	Steinburg-Guinan	100	not provided	not provided	2.90
CTH (2D)	20 cppr	1a'	von Mises	100	1.25	2.37	1.49

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705 *3.4 Case 2 – ¼” Sphere Impact into Basalt Block with Strength*

706 The second case was designed to test the effect of strength on the crater size and momentum  
707 enhancement for brittle materials. Previous benchmarking examined the effect of strength in  
708 metals [Pierazzo *et al.*, 2008], but asteroids are not likely to be made solely of aluminum alloys.  
709 Further, the study of the strength of metals has been studied more extensively than brittle materials,  
710 and thus the number and sophistication of material models for ductile material within shock  
711 hydrocodes is greater than that for geologic materials, though most modern shock codes do include  
712 material models for a variety of geologic materials [e.g., Johnson *et al.*, 1990; Walker and  
713 Anderson, 1992; Collins *et al.* 2004, 2011, 2014, Wünnemann *et al.* 2006 ; Ivanov *et al.* 1997 ;  
714 Melosh *et al.* 1992 ; Schultz and Crawford, 2016]. These models have a range of fidelity, and  
715 require differing amounts of *a priori* knowledge about the simulated material, however. Because  
716 the DART impact is small enough to be in the strength regime on a rocky asteroid, understanding  
717 the effect of brittle material models on crater size and  $\beta$  prediction is important to be able to better  
718 interpret the results from the DART impact. Here, most of the codes examined impacts of ¼”  
719 basalt projectile into a fully-dense basalt half-space with material strength. The results are shown  
720 in Figure 9 and Figure 10. Resolution studies were performed using iSALE and CTH in 2D, and  
721 Spherical in 3D. CTH simulations were also performed in 3D, but only at a resolution of ~6 cppr  
722 (using AMR). CTH simulations were performed using both the “geo” and the “BDL” strength  
723 models. Here, it appears that both crater size and  $\beta$  converge at around 20 cppr for most models.

724

725 General summaries of the results of these comparisons are seen in Table 14 and Table 15. Full  
726 comparisons are shown in Appendix B.

727

728 **Table 14.** Summary of results for CTH, iSALE and Spherical models in both 2D and 3D for Case  
729 2.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (2D)	20 cppr	2	geo	100	2.06	5.03	3.48
CTH (2D)	20 cppr	2	geo	400	1.90	7.41	6.54
CTH (2D)	20 cppr	2	BDL	100	0.85	1.86	1.67
CTH (2D)	20 cppr	2	BDL	300	1.04	2.56	1.56
iSALE (2D)	40 cppr	2	ROCK	100	1.28	3.56	1.8
iSALE (2D)	40 cppr	2	ROCK	308	1.21	4.61	2.25
CTH (3D)	6 cppr	2	geo	100	2.19	4.36	3.83
CTH (3D)	6 cppr	2	BDL	100	0.86	1.78	1.60

Spherical (3D)	nrI = 7	2	von Mises	100	3.24	7.03	5.87
CTH (3D)	6 cpr	2	geo	500	2.06	6.00	5.49
CTH (3D)	6 cpr	2	BDL	500	0.92	2.19	1.44
Spherical (3D)	nrI = 7	2	von Mises	400	3.24	7.03	11.06

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731 Results for iSALE simulations and the CTH BDL simulations (both at a resolution of 20 cpr)  
732 predict similar crater depths (14% difference), though crater diameter exhibits a greater range  
733 (44% difference). When the “geo” model is used, this difference between iSALE and CTH shifts  
734 to 95% and 42% for depth and diameter, respectively. This is likely because the BDL strength  
735 model in CTH is much more similar to the “ROCK” strength model in iSALE than the “geo”  
736 material model, while the “geo” model (as used here) is a more simplified plasticity model.  
737 Similarly to what was seen in *Case 1*, choice of strength model also affects predictions within one  
738 code. When comparing similar models in CTH using the “geo” and “BDL” strength models, values  
739 for crater depth, diameter, and  $\beta$  range within a factor of 2-5 (120-280%). This again illustrates the  
740 importance of choosing an appropriate, or consistent, plasticity model when calculating  
741 momentum transfer and crater size in the strength regime (Figure 10).

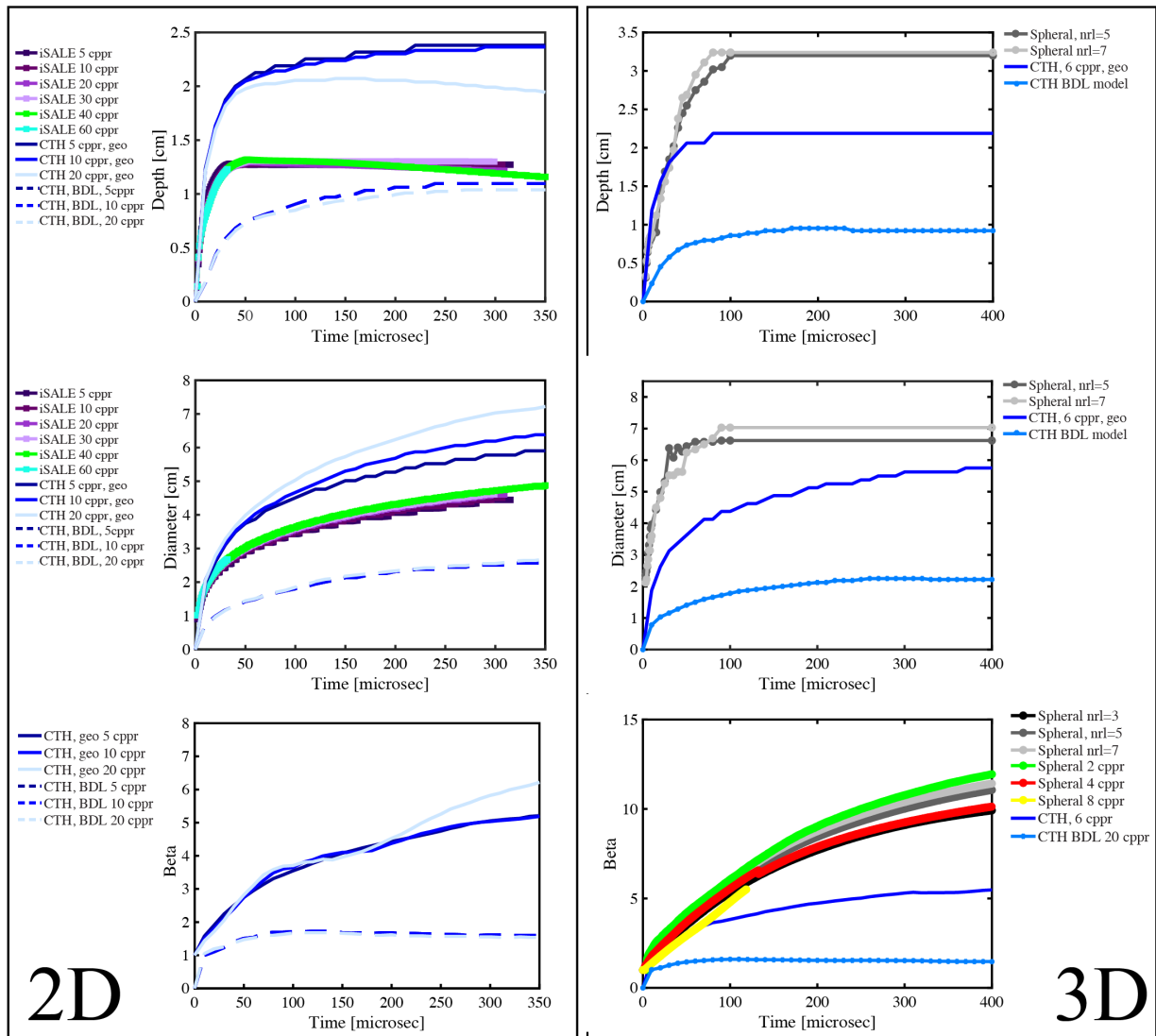
742  
743 It is well documented that if a simulation is underresolved that the results are not necessarily  
744 accurate [e.g., Pierazzo, 2006]. This is consistent with what is seen when examining crater size  
745 and  $\beta$  as a function of resolution (Table 15). In general, crater depth ranges from ~1% - 10%  
746 (except for one set of 2D CTH models), crater diameter predictions are within ~5% of one another  
747 (again, except for one set of 2D CTH simulations), and  $\beta$  predictions are generally within 2-13%  
748 of one another as a function of resolution. Both CTH and Spherical have a set of simulations with  
749 a higher variation in  $\beta$  than is seen in the other simulation sets.

750  
751 **Table 15.** Summary of differences predicted by CTH, iSALE, and Spherical as a function of model  
752 resolution at various times in the calculation for *Case 2*. The range and percent difference in  
753 predicted values across all resolutions is summarized.

Model	Strength	Time [us]	Crater Depth Range [cm]	Crater Diameter Range [cm]	$\beta$ Range	% Difference: Diameter	% Difference: Depth	% Difference: $\beta$
CTH (2D)	geo	100	0.14	0.53	0.2	10.41	6.16	5.36
CTH (2D)	geo	400	0.48	1.38	1.26	18.63	20.33	19.26
CTH (2D)	geo	800	0.79	1.38	1.26	20.9	35.61	13.75
CTH (2D)	BDL	100	0.05	0.06	0.04	2.61	6.14	2.19
CTH (2D)	BDL	300	0.05	0.06	0.06	1.86	5.08	3.51

CTH (2D)	BDL	500	0.05	0.07	0.07	1.69	6.41	4.13
iSALE (2D)	ROCK	100	0.01	0.13	--	3.65	0.78	--
iSALE (2D)	ROCK	~300	0.16	0.06	--	3.47	4.72	--
Spherical (3D)	von Mises	400	0.04	0.41	2.02	5.83	1.23	16.92

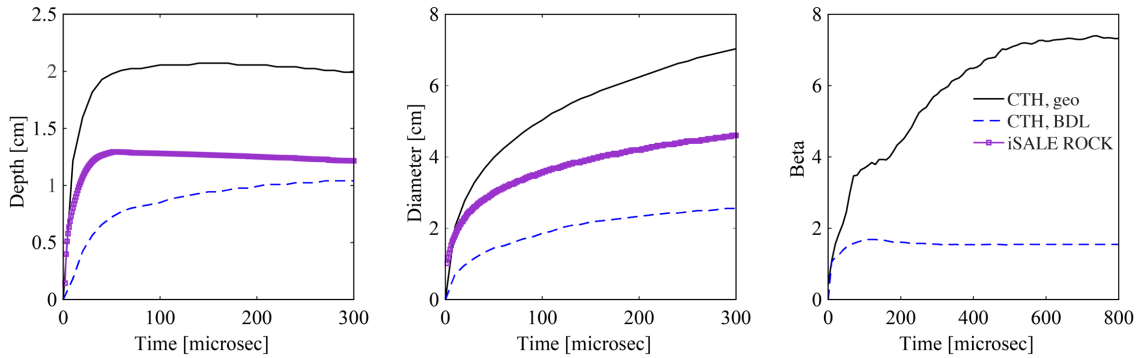
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**Figure 9.** Results of convergence studies in 2D and 3D. Crater size and momentum enhancement predicted for impacts of 1/4" basalt projectile into a basalt half-space at 5 km/s. All simulations included material strength. (left) 2D simulation results for crater depth (top), diameter (middle) and  $\beta$  (bottom) for iSALE and CTH simulations at a variety of resolutions. (right) 3D simulation

763 results for crater depth (top), diameter (middle) and  $\beta$  (bottom) for Spheral and CTH simulations  
 764 at a variety of resolutions. Specific, high-resolution, 2D results are compared in Figure 10.  
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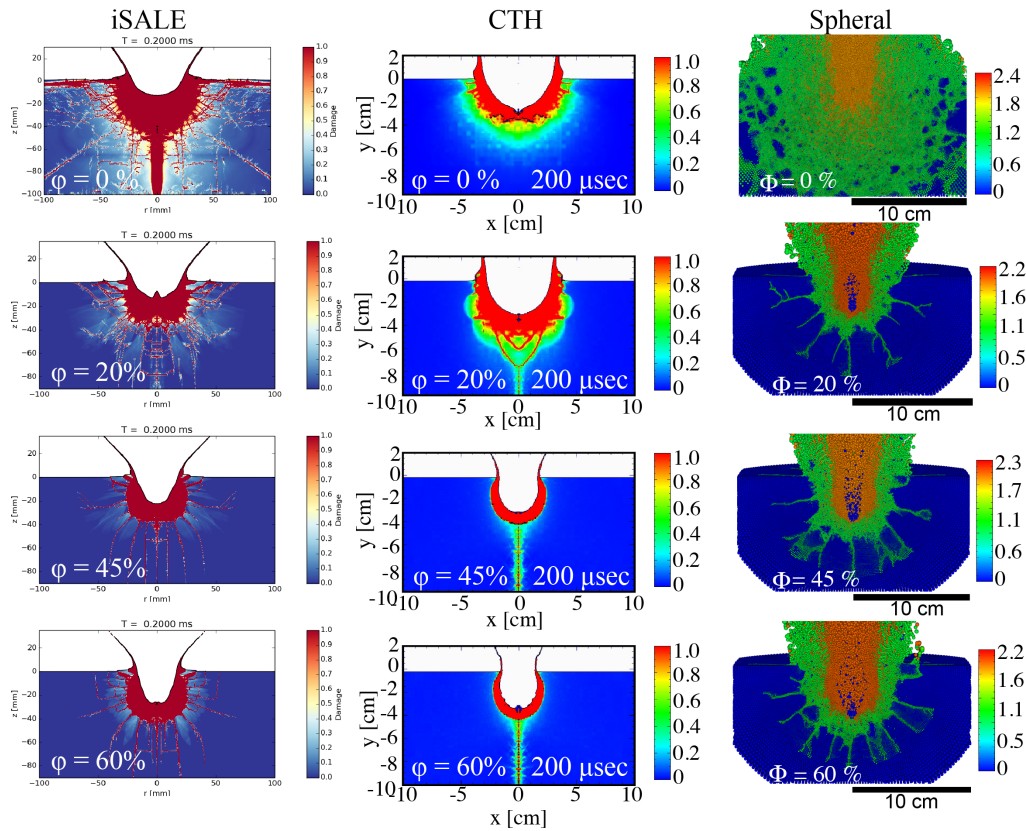
768  
 769 **Figure 10.** Crater depth (left), diameter (middle), and  $\beta$  (right) for three different simulations of a  
 770  $\frac{1}{4}$ " basalt impactor into a basalt half-space at 5 km/s and 90°. All impact parameters are identical  
 771 aside from the chosen strength model, and all simulations have similar resolution. The two models  
 772 that have similar underlying physics, CTH BDL and iSALE "ROCK" result in similar craters. The  
 773 generic pressure-dependent yield surface "geo" results in a substantially different crater size and  
 774 much larger  $\beta$ .  
 775

776 *3.5 Case 3 – Effects of porosity*

777 The third benchmarking case was designed to investigate the effect of porosity models on the crater  
 778 size and momentum enhancement predicted by each code. Natural geologic materials include  
 779 porosity both within and between mineral grains (microporosity) and due to larger scale fractures,  
 780 faults, and pore space within the material. Indeed, meteorite studies find porosities of 10-20% [e.g.,  
 781 *Britt et al, 2002*] and many known small asteroids are estimated to have porosities greater than  
 782 20% [*Britt et al., 2002*]. Specific S-type asteroids are estimated to have porosities ranging from  
 783 15-25%. Indeed, the target for the DART impact, 65803 Didymos is estimated to have a porosity  
 784 of ~18%-20%. Therefore, it is vital to understand the ways in which porosity models affect the  
 785 predicted impact effects.  
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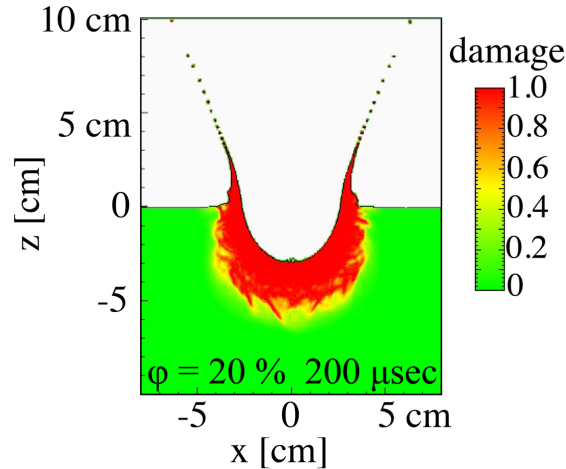
787 Simulations at a variety of porosity values were performed using the CTH, iSALE, and Spheral  
 788 codes. The results are shown in Figure 11, Figure 13, and Figure 14. Both 2-dimensional and 3-  
 789 dimensional simulations were performed using CTH (Figure 11, 12), while iSALE simulations are  
 790 only in 2D and the Spheral simulations are only in 3D. The values for 0% porosity are taken from  
 791 results reported in *Case 2*. In general, simulations with higher porosity result in craters that are  
 792 narrower and deeper than simulations with fully dense material (Figure 11). This is consistent  
 793 across numerical codes. Two-dimensional models, such as those shown in Figure 11, exhibit  
 794 centerline effects at the symmetry axis; here, the increased damage shown along the  $x=0$  line is an  
 795 example. These effects can act to increase pressures and temperatures along the symmetry axis, as  
 796 well as exaggerate crater rebound along the centerline. This is a result of the two-dimensional  
 797 geometry, and is a well-known phenomenon. The only way to remove these sorts of effects is to  
 798 perform three-dimensional simulations (e.g., Figure 12). Note that the centerline effects disappear

799 in the 3D case. The crater shape is altered, and the 3D simulations predict a shallower crater than  
 800 corresponding 2D simulations (Table 16).  
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 804 **Figure 11.** Crater and subsurface damage as a function of porosity. (left) 2D iSALE images,  
 805 (center) 2D CTH images, (right) 3D Spheral images. All images are at 200  $\mu$ sec after impact. Color  
 806 indicates damage, where pristine target material is represented by a value of 0.0 and fully damaged  
 807 material is represented by a value of 1.0 in the scalar damage models (iSALE and CTH) and 3.0  
 808 in the tensor damage model (Spheral; trace of the damage tensor is shown). Centerline effects are  
 809 seen at the symmetry axis in the 2D models. The domain size for the nonporous Spheral target  
 810 extended 15 cm from the impact point, with an inner 9-cm region of uniformly high resolution (5  
 811 cppr), ratioing out to slightly coarser resolution near the edge of the hemispherical domain. The  
 812 porous Spheral targets extended 12 cm from the impact point, with an inner 7-cm region of 5 cppr  
 813 resolution. Greater shock attenuation in the porous models decreases the domain size necessary  
 814 for avoiding edge effects. The number of ASPH particles in each simulation ranged from 1.7 to  
 815 7.6 million. Note that the interior of the crater is filled with ejecta at this time (200  $\mu$ s)  
 816





817  
 818 **Figure 12.** Three-dimensional CTH simulation, showing target damage at 200 usec after impact  
 819 of a ¼” projectile at 5 km/s. The target had 20% porosity. No centerline effects are apparent.  
 820

821 The addition of porosity models in the simulations results in increased scatter in the results from  
 822 different codes (Table 16). Further, the scatter depends on the amount of porosity assumed. For a  
 823 20% porous target, at early times (100 μsec after impact) the predicted crater diameter is the most  
 824 consistent value across codes, with a 28% difference among all simulations (including 2D and 3D).  
 825 Crater depth and predicted momentum enhancement varied more significantly, with a 60-70%  
 826 difference in prediction between codes. This is true for both 2D models compared against one  
 827 another (iSALE to CTH) and for 3D models compared against one another (CTH to Spherical). In  
 828 all comparisons, resolutions are similar across models with similar geometries (2D v. 3D), so the  
 829 scatter is unlikely to be a resolution effect. This scatter decreases with increasing porosity. For a  
 830 target with a 45% porosity, there is a ~30% variation in crater depth across codes, while crater  
 831 diameter and β predictions are much more similar at 6% and 3.5% difference, respectively. When  
 832 only looking at 2D models, crater depth varies by ~25% while diameter varies by 2%. At a target  
 833 porosity of 60%, the variability drops to 16%, 14%, and 4% for predicted crater depth, diameter,  
 834 and β, respectively.

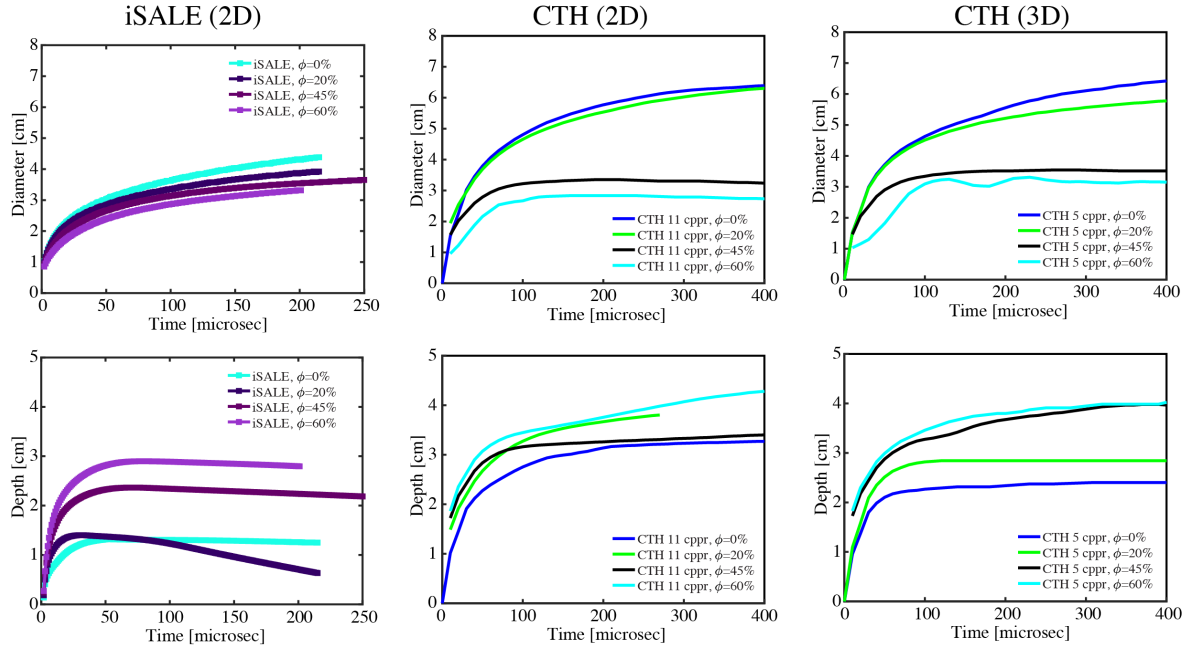
835  
 836 For low values of porosity (0-20%), CTH predicts wider craters than iSALE (Table 16, Figure 13).  
 837 The difference in values narrows at higher porosities. The CTH simulations reported here almost  
 838 uniformly predict deeper craters than similar iSALE simulations. This is likely due to strength  
 839 model choice, as the “geo” and ROCK models are not identical in behavior (Figure 10).  
 840

841  
 842 **Table 16.** Summary of values for various target porosities. When a given result was not supplied  
 843 by specific modelers, it is marked as “not provided” in the table. More complete summaries are  
 844 shown in Appendix B.

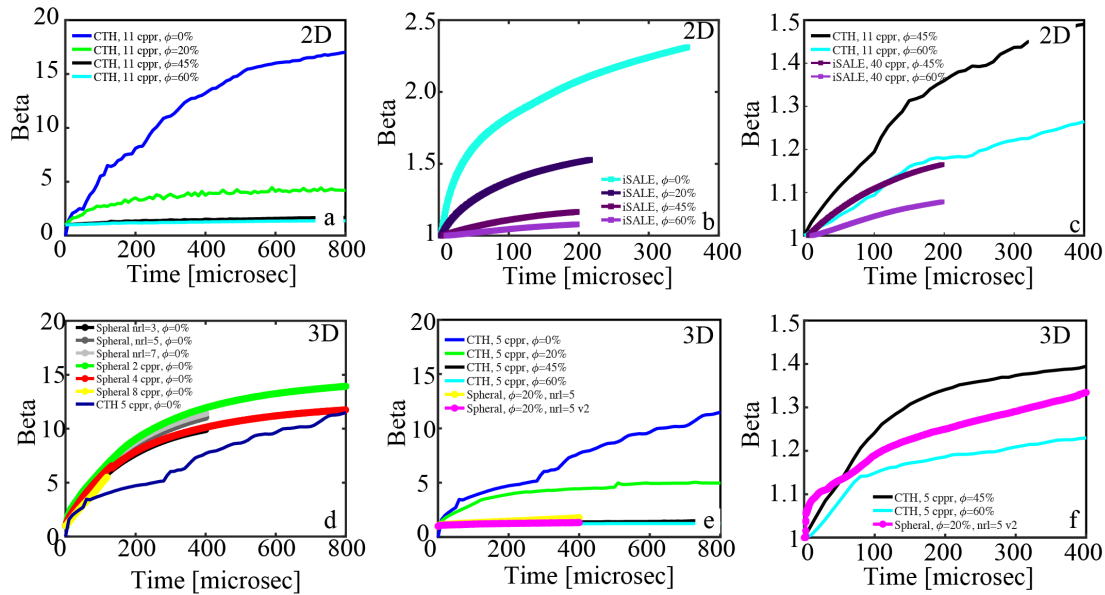
Model	Resolution	Case	Strength	Porosity	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	β
Spherical (3D)	nrI = 5	3	von Mises	20	100	not provided	not provided	1.31

iSALE	40 cppr	3	ROCK	20	100	1.23	3.35	1.38
CTH (2D)	11 cppr	3	geo	20	100	3.29	4.66	2.68
CTH (3D)	5 cppr	3	geo	20	100	2.84	4.51	3.05
iSALE	40 cppr	3	ROCK	45	100	2.34	3.14	1.11
CTH (2D)	11 cppr	3	geo	45	100	3.18	3.21	1.20
CTH (3D)	5 cppr	3	geo	45	100	3.31	3.34	1.24
iSALE	40 cppr	3	ROCK	60	100	2.89	2.87	1.05
CTH (2D)	11 cppr	3	geo	60	100	3.46	2.74	1.10
CTH (3D)	5 cppr	3	geo	60	100	3.42	3.18	1.15
iSALE	40 cppr	3	ROCK	20	200	0.71	3.87	1.51
CTH (2D)	11 cppr	3	geo	20	200	3.67	5.55	3.51
CTH (3D)	5 cppr	3	geo	20	200	2.84	5.21	3.39
iSALE	40 cppr	3	ROCK	45	200	2.24	3.54	1.17
CTH (2D)	11 cppr	3	geo	45	200	3.27	3.35	1.37
CTH (3D)	5 cppr	3	geo	45	200	3.66	3.52	1.34
iSALE	40 cppr	3	ROCK	60	200	2.80	3.32	1.08
CTH (2D)	11 cppr	3	geo	60	200	3.76	2.84	1.19
CTH (3D)	5 cppr	3	geo	60	200	3.80	3.33	1.19

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 849 **Figure 13.** Crater diameter (top) and depth (bottom) at four different target porosities for iSALE  
 850 (2D) and CTH (2D, 3D) simulations. Porosity has a large effect on crater shape and size.  
 851



852  
 853 **Figure 14.** Comparison of  $\beta$  as a function of porosity for (top) 2D simulations, (bottom) 3D and  
 854 simulations. All simulations were of a vertical impact into a porous basalt block at 5 km/s. a) 2D  
 855 CTH simulations showing momentum enhancement as a function of porosity. As porosity  
 856 increases,  $\beta$  decreases. b) 2D iSALE simulations as a function of porosity, showing a similar trend  
 857 to CTH. Note the iSALE used the ‘ROCK’ model here, while CTH simulations were done using  
 858 the ‘geo’ model, which can explain to lower values for  $\beta$ . c) Comparison of high porosities for 2D  
 859 CTH and iSALE simulations. Though they give different results at low porosities, once the  
 860 porosity increases enough both code give much more similar predictions. d) 3D CTH and Spheral

861 simulations at zero porosity; e) 3D CTH and Spheral simulations showing  $\beta$  as a function of  
 862 porosity. Like in 2D,  $\beta$  decreases with increasing porosity. The magnitude of decrease is similar  
 863 between 2D and 3D models. f) Comparison of  $\beta$  predictions for high porosities from 3D CTH  
 864 and Spheral simulations. The two codes use different material behavior and porosity model  
 865 assumptions. Using 20% porosity in Spheral gives a result between the predictions for 45% and  
 866 60% porosity in CTH.

867  
 868 The calculated momentum enhancement is also strongly dependent on the porosity of the target  
 869 (Figure 14). This is expected because significant energy from the impact is expended in pore  
 870 collapse and the amount of ejecta generated from an impact into a porous target is decreased  
 871 compared to a more dense target. For 2D models (Figure 14 a-c), there is a significant difference  
 872 ( $\sim 4X$  at 200  $\mu\text{sec}$ ) between the momentum enhancement predicted by CTH and iSALE at  
 873 porosities of 0-20%. This is likely due to the differences in material models chosen; CTH used the  
 874 “geo” model while iSALE used the “ROCK” model. This difference becomes less noticeable,  
 875 however, as porosity becomes larger, though CTH still predicts higher momentum enhancement  
 876 in this case (Figure 14c). There is also a noticeable difference (15-30%) between the momentum  
 877 enhancement predicted by 3D CTH and Spheral at the porosity most important for the DART  
 878 impact ( $\sim 20\%$ ). Some of this difference is likely due to the way that porosity is modeled in the  
 879 codes: CTH used a  $p$ - $\alpha$  porosity model while Spheral used an  $\epsilon$ - $\alpha$  approach.

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 881 **3.6 Case 4 – Impacts into basalt sphere**

882 *Cases 1-3* involved impacts into a planar, half-space target. This is generally a reasonable  
 883 assumption in situations such as the DART impact where the target size is much larger than the  
 884 projectile. However, some target surface curvature may still be important during the DART impact  
 885 due to the small size of Didymos-B. *Case 4* was designed to better understand how target geometry  
 886 may affect  $\beta$ , specifically for the case of a curved target versus a planar one. Simulations for *Case*  
 887 *4* were performed using CTH, iSALE, and Spheral. A variety of strength models and porosity  
 888 values were simulated (Figure 15 and Figure 16) in both 2D and 3D. As in *Case 3*, increased  
 889 porosity results in deeper, narrower craters and lower  $\beta$  values when all other parameters are kept  
 890 constant (e.g., Table 17). A summary of results for CTH, iSALE, and Spheral simulations at 200  
 891  $\mu\text{sec}$  after impact is shown in Table 17; a full table is shown in Appendix B. Similarly to previous  
 892 cases, when the strength model changes (e.g., using “geo” v. “BDL” in CTH, Figure 15), crater  
 893 shape and size will differ much more dramatically. Momentum enhancement is still lower for  
 894 increased porosity when different strength models are compared. There is not a large difference in  
 895  $\beta$  values for comparable models between 2D and 3D simulations (Figure 16); this difference is  
 896 more pronounced for crater size.

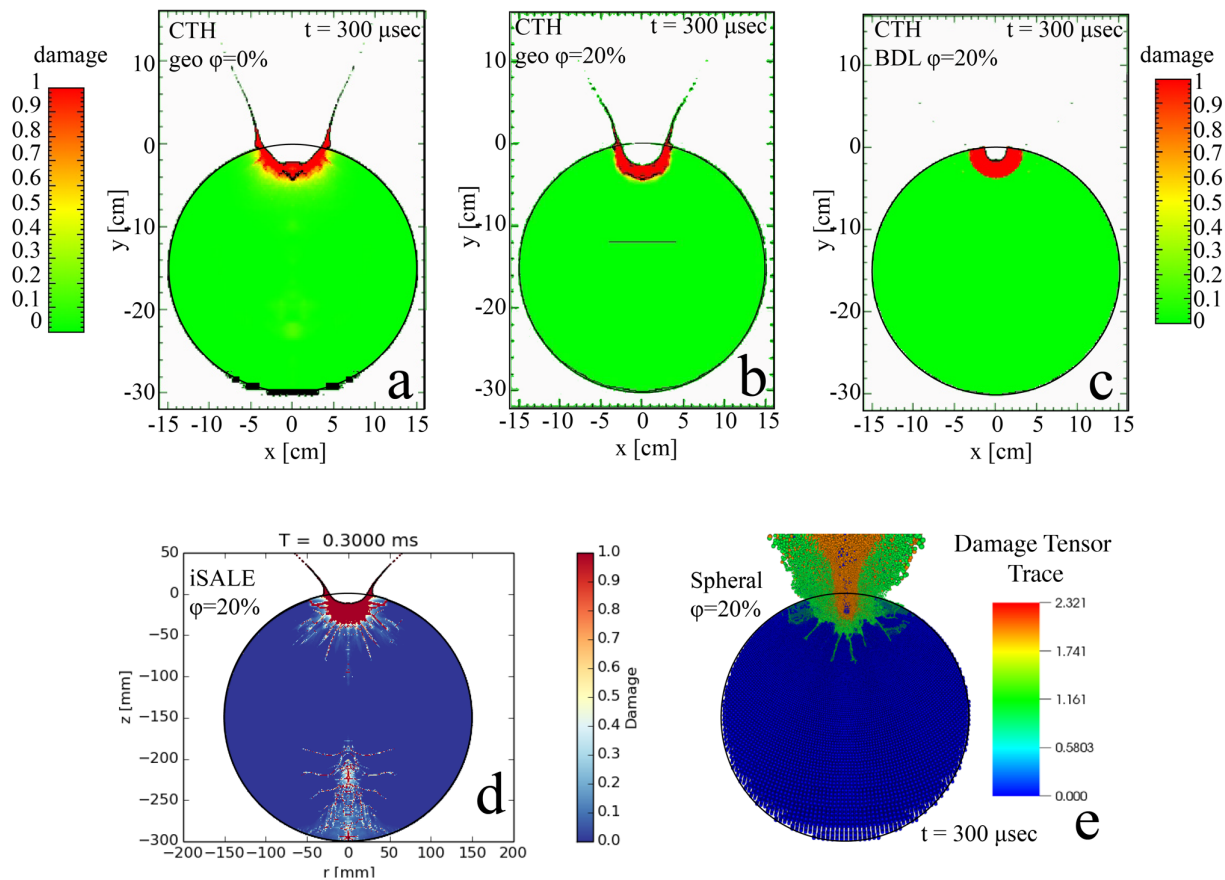
897  
 898 **Table 17.** Summary of values for crater depth, diameter, and  $\beta$  at 200  $\mu\text{sec}$  following impact for a  
 899 variety of porosity values. When a given result was not supplied by specific modelers, it is marked  
 900 as “not provided” in the table.

901

Model	Resolution	Case	Strength	Porosity [%]	Time [ $\mu\text{s}$ ]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (2D)	12 cppr	4	geo	0	200	3.09	7.48	4.43

CTH (2D)	12 cppr	4	geo	20	200	2.74	5.23	2.44
CTH (2D)	25 cppr	4	BDL	10	200	1.46	2.86	1.12
CTH (2D)	25 cppr	4	BDL	20	200	1.63	2.74	1.06
iSALE (2D)	15 cppr	4	ROCK	20	200	1.15	4.19	1.44
CTH (3D)	3 cppr	4	geo	0	200	2.44	5.63	4.92
CTH (3D)	3 cppr	4	geo	20	200	1.31	2.13	1.13
Spherical (3D)	5 cppr	4	von Mises	20	200	not provided	not provided	1.51

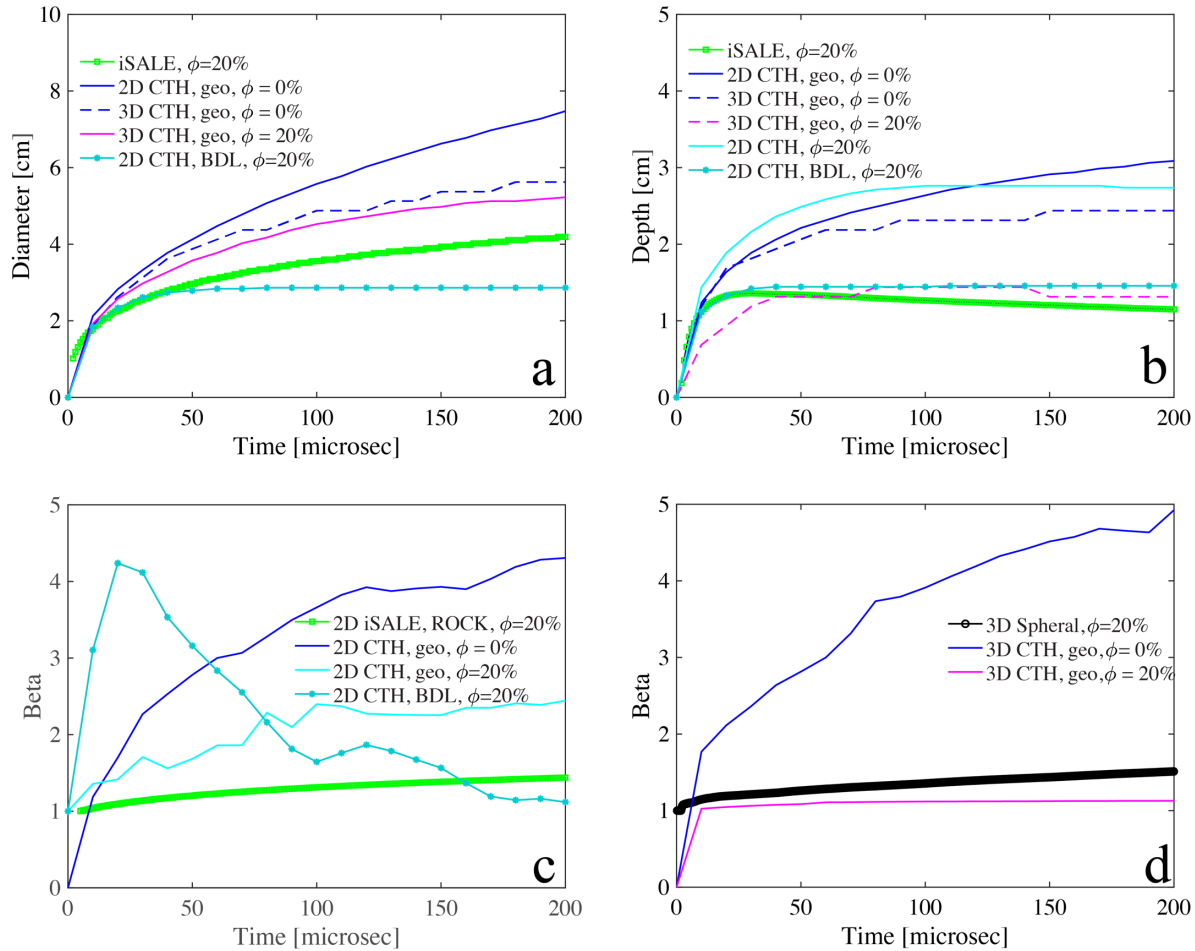
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906 **Figure 15.** Images at 300 usec after impact of a ¼” projectile into a 30-cm basalt sphere at 5 km/s  
 907 at normal incidence. CTH and iSALE simulations are 2D and Spherical simulation is 3D. a) image  
 908 of damage from a CTH simulation using the “geo” strength model and assuming 0% porosity; b)  
 909 image of damage from a CTH simulation using the “geo” strength model and assuming 20%  
 910 porosity. Note that neither the “geo” model or the appended damage model are not designed to

911 track fracture in a rigorous way so the subsurface fracturing is less apparent than in other  
 912 simulations; c) image of damage from a CTH simulation using the “BDL” strength model and  
 913 assuming ~20% porosity; d) image of damage from an iSALE simulation assuming 20% porosity;  
 914 e) Spherical simulation using 20% porosity, showing the trace of the damage tensor.  
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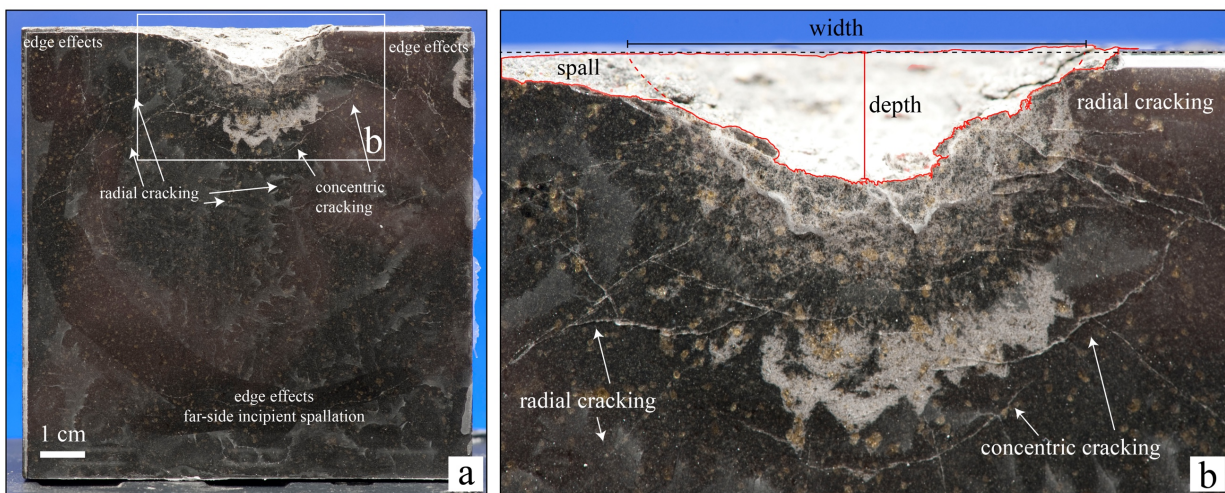
916 **Figure 16.** Graphs of a) crater diameter, b) crater depth, and c,d) momentum enhancement for a  
 917 variety of simulations of an 1/4" sphere impacting into a basalt sphere at 5 km/s. c) 2D iSALE  
 918 simulation for a 20% porous target compared with 3 different 2D CTH simulations using different  
 919 strength models and simulating different target porosity; d) comparisons between 3D CTH and  
 920 Spherical simulations.  
 921

922  
 923 When predicted values are compared across codes, there is some significant scatter. A lot of this  
 924 is, again, due to differences in chosen strength models and porosity values (Figure 16 a,b). When  
 925 these parameters are held constant (or more similar), this scatter decreases but is still present (for  
 926 example: Figure 16c, iSALE ‘ROCK’ compared with CTH ‘BDL’). For instance, there is a ~20%  
 927 difference in predictions of crater diameter between 2D iSALE and CTH (“geo”) simulations.  
 928 Crater depth has a higher scatter, with an ~140% difference in predictions. When the BDL model  
 929 is used in CTH instead, this variation drops to ~40% for in crater depth prediction and ~35% in  
 930 crater diameter prediction. As can be seen in Figure 16, the predicted  $\beta$  value from CTH is highly  
 931 dependent on both strength model choice and porosity. This holds true for 3D simulations as well.

932 Comparisons between 3D CTH and 3D Spheral simulations show an ~25% difference in predicted  
933  $\beta$  for a 20% porous target. This difference is much more pronounced when a fully dense target is  
934 assumed in CTH. These results suggest that plasticity and porosity model choices have a stronger  
935 effect on crater size and momentum enhancement predictions than target geometry (at this scale).  
936

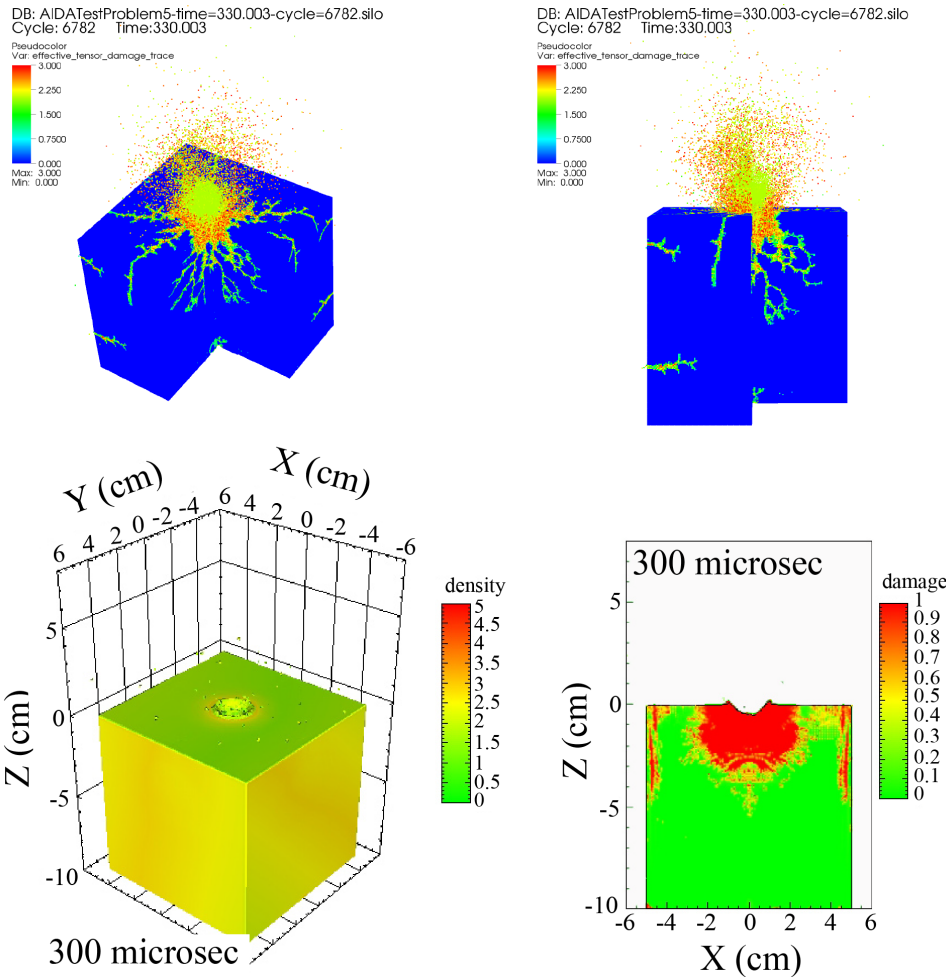
### 937 3.7 Case 5 – Comparison to experiment

938 Cases 1-4 were designed to benchmark various hydrocodes against one another. Case 5, however,  
939 was intended as a validation exercise. Code validation is defined as the process of testing results  
940 against known real-world situations. Often, the validity of a simulation is determined by choices  
941 in material modeling. Here, basic strength parameters and material characteristics as well as impact  
942 conditions were proscribed, but modelers were allowed to choose material models. For example,  
943 simulations using Spheral assumed that some natural porosity is been present in the sample (~7%),  
944 and used a reference density of 3.01 g/cc so that the bulk density of the block was 2.8 g/cc (the  
945 measured value). Results for both CTH and Spheral are shown in Figure 18. These were compared  
946 against an experiment performed at the NASA Ames Vertical Gun Range, shown in Figure 17.  
947 Note that  $\beta$  was not calculated for this experiment and so only final crater size and extent of  
948 fracturing was compared between the experiment and simulations (Table 18). Both codes  
949 performed well in this blind comparison. Simulations using CTH predicted crater width and depth  
950 between 1-11% and 35% different than the experiment, respectively. Simulations using Spheral  
951 predicted crater widths between 9-20% different than measured in the experiment and a diameter  
952 that was 43% different than the measured value. Both codes predicted damage regions roughly  
953 consistent with those measured in the experiment.  
954



955 **Figure 17.** Middle plane of the experiment post-impact, showing crater and fracture patterns. The  
956 dirty appearance of the basalt is epoxy residue from where the PMMA window was removed. a)  
957 10 cm x 10 cm face, along centerline of the crater. There are some edge effects seen in the upper  
958 corners as well as some incipient spallation at the farside of the block. These occurred after the  
959 crater was completely formed, and did not affect the final crater size or shape. b) close-up of the  
960 final crater, showing fracture pattern and crater size. The target was fractured in both the concentric  
961 and radial directions. The black dashed line shows the top surface of the block, the red outline  
962 denotes the final crater edges, and the dashed red line shows the approximate crater shape when  
963

964 the spallation is “removed”. The locations where crater width and depth were measured are noted.  
 965 The olivine phenocrysts are clearly seen and are cut by fractures in some locations.  
 966



967  
 968 **Figure 18.** Results of simulations from Spheral (top) and CTH (bottom) simulations of a 1/4” Pyrex  
 969 impactor into a 10-cm x 10-cm x 10-cm basalt block at 2.1 km/s, showing crater size, density, and  
 970 damage in the target at 300 microsec after impact. Both codes predict significant subsurface  
 971 fracturing, which matches what was seen in the experiment.  
 972

973 **Table 18.** Summary results for CTH and Spheral blind comparisons to an AVGR experiment of a  
 974 2.1 km/s impact into a basalt block

	Crater Width [cm]	Crater depth [cm]	Concentric cracking depth [cm] (approx)	radial cracking extent [cm] (approx)
<b>AVGR experiment 121030</b>	4.2, including spall 3.0-3.4, excluding spall	0.90	~ 3 cm below impact point	4.94



<b>CTH Simulation (330 usec)</b>	3.43, excl. spall	1.4	3-3.5	5.3
<b>Spherical Simulation (330 usec)</b>	2.72	1.6	2.5	5.6

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#### 4. Summary

In support of the AIDA/DART mission, a benchmarking and validation exercise was completed to better understand the expected variability when calculating momentum enhancement and crater size using a variety of codes. This variability in prediction comes both from inherent differences between codes (e.g., type of mesh, types of material models) as well as variations in material models found in different codes. Though many of the codes used in this study had been previously benchmarked against one another for strengthless targets, and validated against experiments [Pierazzo *et al.*, 2008], this was a new effort to determine how the codes compared in the strength regime of cratering.

Some key takeaway points from these comparisons are:

1. Prediction of momentum enhancement is highly resolution dependent, and may require higher resolutions to converge than crater size.
2. When similar strength models are used in different codes, predictions for crater size and momentum enhancement tend to be similar (within 15-20%).
3. The choice of strength model, and the values used for material strength, are significantly more important in the prediction of crater size and momentum enhancement than variation between codes. Material models should be chosen appropriately for the specific applications being evaluated.
4. Material porosity can have large effects on the crater size and significantly affect  $\beta$  predictions. Addition of porosity also results in increased scatter in the results from different codes. This is seen across codes.
5. There is a noticeable difference (15-30%) between the momentum enhancement predicted by CTH and Spherical at porosities important for the DART impact (~20%), which is likely due to the specific porosity model implementations and how they differ in the two codes.
6. For impacts into strengthless targets, crater size shows the least variation between codes compared with momentum enhancement predictions. The variations are similar to what was seen in *Pierazzo et al.* [2008].
7. Hydrocode predictions of momentum enhancement almost uniformly shows a larger variation than linear predictions of crater size (depth and width). This may be due, in part, to contrasting target responses between codes.
8. Both CTH and Spherical performed well in the blind-comparison to an AVGR experiment. Predictions of crater size and extent of fracturing were between 10-40% different than the measured values.

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The Impact Simulation Working Group includes members who use a variety of different codes to simulate the DART impact, including all those compared here. Initially, there was concern that the natural variability in the codes would increase the uncertainty in predicted crater size and

1016 momentum enhancement of Didymos-B from the DART impact. The comparisons shown here  
1017 suggest that this is not the case. In fact, the variability in material model implementation and  
1018 chosen strength and porosity parameters results in larger differences in predicted crater size and/or  
1019 momentum enhancement than using different codes, which has a natural variability of ~15% (e.g.,  
1020 *Pierazzo et al.*, 2008; Case 1a, 1b). Simulation resolution also plays a large role in the consistency  
1021 of prediction, especially when calculating momentum enhancement which requires a higher  
1022 resolution to converge. These findings have implications for DART impact models and simulation  
1023 approach. When using multiple codes, it is vital to select the appropriate (and available) material  
1024 models for specific codes. One should also try to pick material models that are as consistent  
1025 between different codes as possible. When different strength models are chosen in different codes,  
1026 it becomes difficult to understand what causes the large variation in predictions. Alongside  
1027 prescribing a specific material behavior, specific values for strength and resolution of simulations  
1028 should be prescribed and an effort made to maintain them across the team. If equivalent simulations  
1029 are done in CTH, iSALE, and Spheral using the “BDL”, ROCK, and Collins damage models  
1030 [*Schultz and Crawford*, 2016; *Collins et al.*, 2004], respectively, we would expect variations  
1031 consistent with what was seen in this study. If the three different codes are used to simulate impacts  
1032 with varying conditions (e.g., modifying impact angle or target structure), any additional  
1033 variability from that change can then be determined. The specific material model chosen must be  
1034 consistent with the application being evaluated. For instance, an understanding of damage  
1035 propagation may be obtained from most of the material models described above (e.g., Fig. 15), but  
1036 fracture is better tracked using specific models, as seen in Figure 15d. The DART impact  
1037 simulation team will determine a specific desired material parameter set appropriate for the  
1038 Didymos system (including strength and porosity values) as part of the modeling effort, and this  
1039 will be standardized (to the extent possible) across the different codes when making predictions  
1040 for the DART mission. Some variation in predictions will still be expected, but that variation can  
1041 be bracketed by the results shown here.

1042

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1054 LLNL-JRNL-769659-DRAFT. LA-UR-19-22134

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1197 **Appendix A. Summary of parameters used in simulations**

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1199 **Table A.1 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for**  
 1200 **Case 1a: 90° impact of 0.635-cm aluminum sphere into a strengthless aluminum half-space**  
 1201 **at 5 km/s.**

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Case 1a 0.635-cm Al sphere into strengthless Al halfspace	Projectile	Target	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Resolution (cpr or equivalent)	Geometry
CTH	tensile strength (pfrac): 600 Mpa	tensile strength (pfrac): 600 Mpa	Tillotson (see Table 3)	Tillotson (see Table 3)	none	none	5, 10, 20	2DC
CTH	tensile strength (pfrac): 600 Mpa	tensile strength (pfrac): 600 Mpa	Tillotson (see Table 3)	Tillotson (see Table 3)	none	none	3,5	3D
Spheral	--	--	Tillotson (see Table 3)	Tillotson (see Table 3)			5-7	2D
iSALE	--	--	Tillotson Al-1100	Tillotson Al-1100	none	none	40	2D
RAGE	--	--	Tillotson	Tillotson	none	none	3,5,10,20	2D
PAGOSA	--	--	Tillotson	Tillotson	none	none	3,5,10,20	2D

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1205 **Table A.2 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for**  
 1206 **Case 1a': 90° impact of 0.635-cm aluminum sphere into a constant-strength aluminum half-**  
 1207 **space at 5 km/s.**

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Case 1a' - constant strength 0.635-cm Al sphere into Al halfspace	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Resolution (cpr or equivalent)	Geometry
CTH	Mie-Gruneisen Al-6061	Mie-Gruneisen Al-6061	von Mises Yield strength = 275 MPa Poissons ratio = 0.33 Tmelt = 11604 K pfrac (tensile strength) = 600 MPa	von Mises Yield strength = 275 MPa Poissons ratio = 0.33 Tmelt = 11604 K pfrac (tensile strength) = 600 MPa	5, 20 20	2D
CTH	Mie-Gruneisen Al-6061	Mie-Gruneisen Al-6061	von Mises Yield strength = 275 MPa Poissons ratio = 0.33 Tmelt = 11604 K pfrac (tensile strength) = 600 MPa	von Mises Yield strength = 275 MPa Poissons ratio = 0.33 Tmelt = 11604 K pfrac (tensile strength) = 600 MPa	3,5	3D
Spheral	Tillotson	Tillotson	von Mises Yield strength = 275 MPa Poissons ratio = 0.33	von Mises Yield strength = 275 MPa Poissons ratio = 0.33	5	3D
iSALE			von Mises equivalent stress = 275 MPa Minimum pressure = 2.44 GPa	von Mises equivalent stress = 275 MPa Minimum pressure = 2.44 GPa	5,10,20,40,60	2D
RAGE	Tillotson	Tillotson	Steinburg-Guinan	Steinburg-Guinan	3,5,10,20	2D
PAGOSA	Tillotson	Tillotson	Steinburg-Guinan	Steinburg-Guinan	3,5,10,20	2D

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**Table A.3 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for**  
**Case 1b: 90° impact of 0.635-cm aluminum sphere into a strengthless basalt half-space at 5**

1214 km/s. The Tillotson EOS with values for basalt is named “gabbroic anorthosite” in the CTH  
 1215 distribution, and labeled accordingly here.

Case 1b 0.635-cm basalt sphere into strengthless basalt halfspace	Projectile	Target	Projectile EOS	Target EOS	Resolution (cpr or equivalent)	Geometry
CTH	spall strength = 80 MPa	spall strength = 80 MPa	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	5	2DC
CTH	spall strength = 80 MPa	spall strength = 80 MPa	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	5	3DR
Spherical			Tillotson (see Table 3)	Tillotson (see Table 3)	5-7	3DR
RAGE			Tillotson	Tillotson		
PAGOSA			Tillotson	Tillotson		

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**Table A.4 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for Case 2: 90° impact of 0.635-cm basalt sphere into a basalt half-space at 5 km/s. The Tillotson EOS with values for basalt is named “gabbroic anorthosite” in the CTH distribution, and labeled accordingly here.**

Case 2 0.635-cm basalt sphere into basalt halfspace	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Damage model	Porosity Model	Resolution (cpr or equivalent)	Geometry
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = -80 MPa, Weibull Modulus = 10	none	5, 10, 20	2DC
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 Mpa, pfrac = 80 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = -80 MPa, Weibull Modulus = 10	none	5	3D
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Brittle Damage with Localized Thermal Softening (BDL) pfrac = 80 MPa Y0 = 36.4 MPa, YM = 2.94 GPa, CFI = 1.8, CFD = 0.6, PBD = 4.91 GPa, PBP1 = 9.38 GPa, PBP2 = 18.75 GPa	Brittle Damage with Localized Thermal Softening (BDL) pfrac = 80 MPa Y0 = 36.4 MPa, YM = 2.94 GPa, CFI = 1.8, CFD = 0.6, PBD = 4.91 GPa, PBP1 = 9.38 GPa, PBP2 = 18.75 GPa	BDL	none	5, 10, 20	2DC
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Brittle Damage with Localized Thermal Softening (BDL) pfrac = 80 MPa Y0 = 36.4 MPa, YM = 2.94 GPa, CFI = 1.8, CFD = 0.6, PBD = 4.91 GPa, PBP1 = 9.38 GPa, PBP2 = 18.75 GPa	Brittle Damage with Localized Thermal Softening (BDL) pfrac = 80 MPa Y0 = 36.4 MPa, YM = 2.94 GPa, CFI = 1.8, CFD = 0.6, PBD = 4.91 GPa, PBP1 = 9.38 GPa, PBP2 = 18.75 GPa	BDL	none	5	3D
Spheral	Tillotson	Tillotson	von Mises Y0=600 Mpa, G=29 Gpa	von Mises Y0=600 Mpa, G=29 Gpa	Tensor generalization of the Benz-Asphaug implementation of Grady-Kipp damage (Benz and Asphaug, 1994) Weibull constants: k=5e24 cm-3, m=9.0			
iSALE	Tillotson	Tillotson	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7GPa	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7GPa	Defined in Collins et al., 2004 Damage parameters listed with plasticity model.	none	40	2D



**Table A.5 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for Case 3: 90° impact of 0.635-cm basalt sphere into a porous basalt half-space at 5 km/s.**

Case 3 0.635-cm basalt sphere into basalt halfspace with porosity	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Damage model	Porosity Model	Resolution (cpr or equivalent)	Geometry
CTH	Sesame 7360	Sesame 7360	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = 80 MPa, Weibull Modulus = 10	p-alpha model	5, 10, 20	2DC
CTH	Sesame 7360	Sesame 7360	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 Mpa, pfrac = 80 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = 80 MPa, Weibull Modulus = 10	p-alpha model	5	3D
Spheral	Tillotson - basalt	Tillotson - basalt	von Mises Y0=600 Mpa, G=29 Gpa	von Mises Y0=600 Mpa, G=29 Gpa	Tensor generalization of the Benz- Asphaug implementation of Grady-Kipp damage (Benz and Asphaug, 1994) Weibull constants: k=5e24 cm-3, m=9.0	epsilon-alpha model epsilon-c= 0.0, epsilon-chi=-0.4, and kappa= 0.8	5	
iSALE	Tillotson - basalt	Tillotson - basalt	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7GPa	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7 GPa	Defined in Collins et al., 2004 Damage parameters listed with plasticity model.	epsilon-alpha model Porosity model parameter: Initial distension (porosity) 1.25; 1.82; 2.5 (20%, 45%, 60%) Elastic threshold -1.00D-03 Transition distension 1.1 Exponential coeff. 0.8 for 20% porosity, 0.98 for 45 and 60% porosity; Sound speed ratio 1.0 for 20% porosity, 0.5 for 45% porosity, 0.4 for 60% porosity	40	2D

**Table A.6 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for Case4: 90° impact of 0.635-cm basalt sphere into a porous basalt sphere at 5 km/s. The Tillotson EOS with values for basalt is named “gabbroic anorthosite” in the CTH distribution, and labeled accordingly here.**

Case 4 0.635-cm basalt sphere into 30-cm basalt sphere with 0- 20% porosity	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Damage model	Porosity Model	Resolution (cpr or equivalent)	Geometry
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = -80 MPa, Weibull Modulus = 10	none	5, 10, 20	2DC
CTH	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Tillotson "Gabbroic Anorthosite" R0 = 2.8 * g/cc, fully dense basalt A = 2.67E11 * erg/cc = dyne/cm <sup>2</sup> B = 2.67e11 * erg/cc = dyne/cm <sup>2</sup> A0 = 0.5 * (default value) B0 = 1.50 * (default value) ALFA = 5.0 * (default value) BET = 5.0 * (default value) EIV = 4.72e10 * erg/g (default value) ECV = 1.82e11 * erg/g (default value) E0 = 4.87e12 * erg/g (default value)	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 Mpa, pfrac = 80 MPa	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Johnson-Cook Fracture D1 = 0.05, Tmelt = 0.16 eV, JFPF0 = -80 MPa, Weibull Modulus = 10	none	5	3D
Spheral	Tillotson - basalt	Tillotson - basalt	von Mises Y0=600 Mpa, G=29 Gpa	von Mises Y0=600 Mpa, G=29 Gpa	Tensor generalization of the Benz-Asphaug implementation of Grady-Kipp damage (Benz and Asphaug, 1994) Weibull constants: k=5e24 cm-3, m=9.0	epsilon-alpha model epsilon-e= 0.0, epsilon- chi=-0.4, and kappa= 0.8	5	
iSALE	Tillotson - basalt	Tillotson - basalt	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7GPa	"ROCK" Strength parameters: Cohesion of intact material 21.0 MPa (calculated from QS compressive strength) Coeff. of internal friction for intact material 1.8 Limiting strength for intact material 1.7 GPa Cohesion of damaged material 0.0 Coeff. of internal friction for damaged material 0.6 Limiting strength for damaged material 1.7GPa	Defined in Collins et al., 2004 Damage parameters listed with plasticity model.	epsilon-alpha model Porosity model parameter: Initial distension (porosity) 1.25 Elastic threshold - 1.00D-03 Transition distension 1.1 Exponential coeff. 0.8 Sound speed ratio 1.0 for 20% porosity	40	2D

**Table A.7 Simulation parameters for CTH, Spheral, iSALE-2D, RAGE, and PAGOSA for Case 5: 90° impact of 0.635-cm Pyrex sphere into a 10-cm basalt block at 2.1 km/s**

Case 5: 0.635 cm Pyrex projectile into a 10-cm basalt block, 2.1 km/s	Projectile	Target	Projectile EOS	Target EOS	Projectile Plasticity Model	Target Plasticity Model	Damage model	Porosity Model	Resolution (cpr or equivalent)	Geometry
CTH	Pyrex	Basalt	Mie-Gruneisen	Tillotson "Gabbroic Anorthosite" $R0 = 2.8$ * g/cc, fully dense basalt $A = 2.67E11$ * erg/cc = dyne/cm <sup>2</sup> $B = 2.67e11$ * erg/cc = dyne/cm <sup>2</sup> $A0 = 0.5$ * (default value) $B0 = 1.50$ * (default value) $ALFA = 5.0$ * (default value) $BET = 5.0$ * (default value) $EIV = 4.72e10$ * erg/g (default value) $ECV = 1.82e11$ * erg/g (default value) $E0 = 4.87e12$ * erg/g (default value)	Pressure-dependent Yield Yield = 10 GPa, poisson = 0.2, dydp = 0.5, yzero = 900 Mpa, Tmelt = 0.25 eV	Pressure-dependent Yield Yield = 1 GPa, poisson = 0.25, dydp = 0.5, yzero = 40 MPa	Projectile: Johnson-Cook Fracture $D1 = 0.05$ , $T_{melt} = 0.25$ eV, $JFPF0 = -1.8$ GPa, Weibull Modulus = 10  Target: Johnson-Cook Fracture $D1 = 0.05$ , $T_{melt} = 0.16$ eV, $JFPF0 = -80$ MPa, Weibull Modulus = 10	none	2D: 12, 3D: 2,5	2D, 3D
Spheral	Pyrex	Basalt	Mie-Gruneisen (Stickle and Schultz, 2012)	Tillotson (see Table 3)		von Mises $y0 = 600$ Mpa, $G=29$ Gpa	Tensor generalization of the Benz-Asphaug implementation of Grady-Kipp damage (Benz and Asphaug, 1994) Weibull constants: $k=5e24$ cm-3, $m=9.0$	7% porosity	5	3D

## Appendix B. Summary of values as a function of time

**Table B.1.** Summary of crater depth, diameter, and calculated momentum transfer efficiency for Case 1a. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
iSALE	40 cppr	1a	none	100	3.05	5.37	4.02
iSALE	40 cppr	1a	none	400	4.87	8.87	8.68
CTH (2D)	20 cppr	1a	none	100	3.20	5.54	4.54
CTH (2D)	20 cppr	1a	none	400	5.18	9.19	10.22
CTH (2D)	20 cppr	1a	none	800	6.71	11.83	12.57
CTH (3D)	6 cppr	1a	none	100	3.19	5.45	3.68
CTH (3D)	6 cppr	1a	none	400	5.19	9.02	5.19
CTH (3D)	6 cppr	1a	none	800	6.53	11.60	5.82
RAGE	2.5 cppr	1a	none	100	not provided	not provided	2.49
RAGE	5 cppr	1a	none	100	not provided	not provided	4.63
RAGE	10 cppr	1a	none	100	not provided	not provided	5.15
RAGE	20 cppr	1a	none	100	not provided	not provided	5.40
RAGE	2.5 cppr	1a	none	400	not provided	not provided	5.20
RAGE	5 cppr	1a	none	400	not provided	not provided	7.42
RAGE	10 cppr	1a	none	400	not provided	not provided	8.26
RAGE	20 cppr	1a	none	400	not provided	not provided	9.14
Spheral (2D)	nrl=5	1a	none	100	1.17	2.36	3.68

Spheral (2D)	nrl=10	1a	none	100	1.2	2.36	5.17
Spheral (2D)	nrl=20	1a	none	100	not provided	not provided	5.92
Spheral (2D)	nrl=40	1a	none	100	not provided	not provided	6.90
Spheral (3D)	nrl=3	1a	none	100	not provided	not provided	1.95
Spheral (3D)	nrl=5	1a	none	100	2.69	4.24	3.12
Spheral (3D)	nrl=7	1a	none	100	2.8	4.42	3.87
PAGOSA	2.5 cppr	1a	none	100	3.27	6.13	9.41
PAGOSA	5 cppr	1a	none	100	3.26	5.65	6.99
PAGOSA	10 cppr	1a	none	100	3.17	5.51	6.63
PAGOSA	20 cppr	1a	none	100	3.17	5.47	6.45
PAGOSA	2.5 cppr	1a	none	400	5.71	10.08	13.69
PAGOSA	5 cppr	1a	none	400	5.08	9.30	11.05
PAGOSA	10 cppr	1a	none	400	5.13	9.17	10.54
PAGOSA	20 cppr	1a	none	400	5.10	9.12	10.16
PAGOSA	2.5 cppr	1a	none	800	6.76	12.85	19.75
PAGOSA	5 cppr	1a	none	800	6.49	11.91	12.52
PAGOSA	10 cppr	1a	none	800	6.61	11.75	11.50
PAGOSA	20 cppr	1a	none	800	6.73	11.72	10.94

**Table B.2.** Summary of crater depth, diameter, and calculated momentum transfer efficiency for modified Case 1a. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
PAGOSA	2.5 cppr	1a	Steinburg-Guinan	100	2.58	1.15	1.03
PAGOSA	5 cppr	1a	Steinburg-Guinan	100	2.20	1.08	1.03

PAGOSA	10 cppr	1a	Steinburg-Guinan	100	2.08	1.09	1.09
PAGOSA	20 cppr	1a	Steinburg-Guinan	100	2.06	1.09	1.03
PAGOSA	2.5 cppr	1a	Steinburg-Guinan	400	2.56	1.18	1.00
PAGOSA	5 cppr	1a	Steinburg-Guinan	400	2.19	1.08	1.20
PAGOSA	10 cppr	1a	Steinburg-Guinan	400	2.08	1.08	1.02
PAGOSA	20 cppr	1a	Steinburg-Guinan	400	1.06	0.98	1.01
RAGE	2.5 cppr	1a	Steinburg-Guinan	100	not provided	not provided	2.75
RAGE	5 cppr	1a	Steinburg-Guinan	100	not provided	not provided	2.78
RAGE	10 cppr	1a	Steinburg-Guinan	100	not provided	not provided	2.85
RAGE	20 cppr	1a	Steinburg-Guinan	100	not provided	not provided	2.90
RAGE	2.5 cppr	1a	Steinburg-Guinan	400	not provided	not provided	3.81
RAGE	5 cppr	1a	Steinburg-Guinan	400	not provided	not provided	3.54
RAGE	10 cppr	1a	Steinburg-Guinan	400	not provided	not provided	3.40
RAGE	20 cppr	1a	Steinburg-Guinan	400	not provided	not provided	3.31
RAGE	2.5 cppr	1a	Steinburg-Guinan	800	not provided	not provided	4.93
RAGE	5 cppr	1a	Steinburg-Guinan	800	not provided	not provided	4.24
RAGE	10 cppr	1a	Steinburg-Guinan	800	not provided	not provided	3.76
RAGE	20 cppr	1a	Steinburg-Guinan	800	not provided	not provided	--

iSALE	40 cppr	1a	Johnson-Cook	100	1.37	2.56	not provided
iSALE	40 cppr	1a	Johnson-Cook	370	1.18	2.59	not provided
iSALE (grid)	60 cppr	1a'	von Mises	80	1.19	2.36	1.00
iSALE (cell)	60 cppr	1a'	von Mises	80	1.19	2.36	1.41
CTH (2D)	5 cppr	1a'	von Mises	80	1.24	2.22	1.23
CTH (2D)	10 cppr	1a'	von Mises	80	1.25	2.32	1.28
CTH (2D)	20 cppr	1a'	von Mises	80	1.25	2.37	1.57
CTH (2D)	5 cppr	1a'	von Mises	100	1.24	2.22	1.22
CTH (2D)	10 cppr	1a'	von Mises	100	1.25	2.32	1.28
CTH (2D)	20 cppr	1a'	von Mises	100	1.25	2.37	1.49
CTH (3D)	5 cppr	1a'	von Mises	40	1.26	2.29	1.36
Spheral (3D)	nrl=3	1a'	von Mises	30	not provided	not provided	1.00
Spheral (3D)	nrl=5	1a'	von Mises	30	1.26	2.10	1.05
Spheral (3D)	nrl=6	1a'	von Mises	100	1.26	2.10	--
Spheral (3D)	nrl=7	1a'	von Mises	30	1.20	2.12	1.11
Spheral (3D)	nrl=7	1a'	von Mises	100	1.20	2.12	--
Spheral (2D)	nrl=5	1a'	von Mises	24	1.17	2.36	1.15
Spheral (2D)	nrl=6	1a'	von Mises	100	1.18	2.36	--
Spheral (2D)	nrl=10	1a'	von Mises	35	not provided	not provided	1.15
Spheral (2D)	nrl=20	1a'	von Mises	35	not provided	not provided	1.25
Spheral (2D)	nrl=40	1a'	von Mises	35	not provided	not provided	1.23

**Table B.3.** Summary of crater depth, diameter, and calculated momentum transfer efficiency for Case 2. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (2D)	5 cppr	2	geo	100	2.19	4.51	3.54
	10 cppr	2	geo	100	2.17	4.67	3.68
	20 cppr	2	geo	100	2.06	5.03	3.48
CTH (2D)	5 cppr	2	geo	400	2.38	6.03	5.37
	10 cppr	2	geo	400	2.37	6.57	5.28
	20 cppr	2	geo	400	1.90	7.41	6.54
CTH (2D)	5 cppr	2	geo	800	2.19	6.67	6.32
	10 cppr	2	geo	800	2.21	7.14	6.88
	20 cppr	2	geo	800	1.42	8.43	7.33
CTH (2D)	5 cppr	2	BDL	100	0.90	1.81	1.71
	10 cppr	2	BDL	100	0.90	1.81	1.71
	20 cppr	2	BDL	100	0.85	1.86	1.67
CTH (2D)	5 cppr	2	BDL	300	1.10	2.51	1.61
	10 cppr	2	BDL	300	1.10	2.51	1.61
	20 cppr	2	BDL	300	1.04	2.56	1.56
CTH (2D)	5 cppr	2	BDL	500	1.09	2.76	1.62
	10 cppr	2	BDL	500	1.09	2.76	1.62
	20 cppr	2	BDL	500	1.02	2.81	1.55
iSALE	5 cppr	2	ROCK	100	1.27	3.43	not provided
	10 cppr	2	ROCK	100	1.28	3.49	not provided
	20 cppr	2	ROCK	100	1.28	3.56	not provided
	30 cppr	2	ROCK	100	1.30	3.60	not provided
	40 cppr	2	ROCK	100	1.30	3.62	1.18



iSALE	5 cpr	2	ROCK	315	1.27	4.45	not provided
	10 cpr	2	ROCK	307	1.27	4.51	not provided
	20 cpr	2	ROCK	308	1.21	4.61	not provided
	30 cpr	2	ROCK	299	1.30	4.61	not provided
	40 cpr	2	ROCK	315	1.18	4.78	2.25
CTH (3D)	6 cpr	2	geo	100	2.19	4.36	3.83
	6 cpr	2	geo	300	2.19	5.63	5.20
	6 cpr	2	geo	500	2.06	6.00	5.49
CTH (3D)	6 cpr	2	BDL	100	0.86	1.78	1.60
	6 cpr	2	BDL	300	0.92	2.25	1.53
	6 cpr	2	BDL	500	0.92	2.19	1.44
Spheral (3D)	nrl = 3	2	von Mises	100	not provided	not provided	5.33
	nrl = 3	2	von Mises	400	not provided	not provided	9.92
	nrl = 5	2	von Mises	100	3.20	6.62	5.72
	nrl = 5	2	von Mises	400	3.20	6.62	11.42
	nrl = 7	2	von Mises	100	3.24	7.03	5.87
	nrl = 7	2	von Mises	400	3.24	7.03	11.06
Spheral (3D)	2 cpr	2	von Mises	100	not provided	not provided	6.05
	2 cpr	2	von Mises	400	not provided	not provided	11.94
Spheral (3D)	4 cpr	2	von Mises	100	not provided	not provided	5.55
	4 cpr	2	von Mises	400	not provided	not provided	10.13

Spherical (3D)	8 cppr	2	von Mises	100	not provided	not provided	4.80
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**Table B.4.** Summary of crater depth, diameter, and calculated momentum transfer efficiency for Case 3. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Porosity	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
Spherical (3D)	nrl = 5	3	von Mises	20	100	not provided	not provided	1.31
Spherical (3D)	nrl = 5 v2	3	von Mises	20	100	not provided	not provided	1.19
Spherical (3D)	nrl = 5	3	von Mises	20	200	not provided	not provided	1.46
Spherical (3D)	nrl = 5 v2	3	von Mises	20	200	not provided	not provided	1.25
iSALE	40 cppr	3	ROCK	20	100	1.23	3.35	1.38
iSALE	40 cppr	3	ROCK	45	100	2.34	3.14	1.11
iSALE	40 cppr	3	ROCK	60	100	2.89	2.87	1.05
iSALE	40 cppr	3	ROCK	20	200	0.71	3.87	1.51
iSALE	40 cppr	3	ROCK	45	200	2.24	3.54	1.17
iSALE	40 cppr	3	ROCK	60	200	2.80	3.32	1.08
CTH (2D)	11 cppr	3	geo	20	100	3.29	4.66	2.68
CTH (2D)	11 cppr	3	geo	45	100	3.18	3.21	1.20
CTH (2D)	11 cppr	3	geo	60	100	3.46	2.74	1.10
CTH (2D)	11 cppr	3	geo	20	200	3.67	5.55	3.51
CTH (2D)	11 cppr	3	geo	45	200	3.27	3.35	1.37
CTH (2D)	11 cppr	3	geo	60	200	3.76	2.84	1.19

CTH (2D)	11 cppr	3	geo	20	500	3.36	6.49	4.01
CTH (2D)	11 cppr	3	geo	45	500	3.48	3.16	1.54
CTH (2D)	11 cppr	3	geo	60	500	4.44	2.65	1.31
CTH (3D)	5 cppr	3	geo	20	100	2.84	4.51	3.05
CTH (3D)	5 cppr	3	geo	45	100	3.31	3.34	1.24
CTH (3D)	5 cppr	3	geo	60	100	3.42	3.19	1.15
CTH (3D)	5 cppr	3	geo	20	200	2.84	5.21	3.39
CTH (3D)	5 cppr	3	geo	45	200	3.66	3.52	1.34
CTH (3D)	5 cppr	3	geo	60	200	3.80	3.33	1.19
CTH (3D)	5 cppr	3	geo	20	500	2.78	5.92	4.58
CTH (3D)	5 cppr	3	geo	45	500	4.01	3.49	1.41
CTH (3D)	5 cppr	3	geo	60	500	3.98	3.05	1.24

**Table B.5.** Summary of crater depth, diameter, and calculated momentum transfer efficiency for Case 4. When a given result was not supplied by specific modelers, it is marked as “not provided” in the table.

Model	Resolution	Case	Strength	Porosity	Time [us]	Crater Depth [cm]	Crater Diameter [cm]	$\beta$
CTH (2D)	12 cppr	4	geo	0	100	2.64	5.575	3.90
CTH (2D)	12 cppr	4	geo	0	200	3.09	7.475	4.43
CTH (2D)	12 cppr	4	geo	0	500	3.64	11.275	5.15
CTH (2D)	12 cppr	4	geo	20	100	2.76	4.525	2.40
CTH (2D)	12 cppr	4	geo	20	200	2.74	5.225	2.44
CTH (2D)	12 cppr	4	geo	20	500	2.64	5.575	3.11
CTH (2D)	25 cppr	4	BDL	10	100	1.44	2.8625	1.64
CTH (2D)	25 cppr	4	BDL	10	200	1.46	2.8625	1.12
CTH (2D)	25 cppr	4	BDL	10	500	1.46	2.8625	1.04
CTH (2D)	25 cppr	4	BDL	20	100	1.63	2.7385	1.07

CTH (2D)	25 cppr	4	BDL	20	200	1.63	2.7385	1.06
CTH (2D)	25 cppr	4	BDL	20	460	1.62	2.7385	1.02
CTH (3D)	3 cppr	4	geo	0	100	2.31	4.8756	3.91
CTH (3D)	3 cppr	4	geo	0	200	2.44	5.625	4.92
CTH (3D)	3 cppr	4	geo	0	500	2.56	6.75	5.16
CTH (3D)	3 cppr	4	geo	20	100	1.44	2.125	1.12
CTH (3D)	3 cppr	4	geo	20	200	1.31	2.125	1.13
CTH (3D)	3 cppr	4	geo	20	300	1.19	2	1.13
iSALE	15 cppr	4	ROCK	20	100	1.27	3.56	not provided
iSALE	15 cppr	4	ROCK	20	200	1.15	4.19	not provided
iSALE	15 cppr	4	ROCK	20	339	0.99	4.66	not provided
Spheral (3D)	5 cppr	4	von Mises	20	100	not provided	not provided	1.36
Spheral (3D)	5 cppr	4	von Mises	20	200	not provided	not provided	1.51
Spheral (3D)	5 cppr	4	von Mises	20	216	not provided	not provided	1.53