



Publication Year	2020
Acceptance in OA	2025-03-20T09:02:43Z
Title	An endogenic origin of cerean organics
Authors	Bowling, T. J., Johnson, B. C., Marchi, S., DE SANCTIS, MARIA CRISTINA, Castillo-Rogez, J. C., Raymond, C. A.
Publisher's version (DOI)	10.1016/j.epsl.2020.116069
Handle	http://hdl.handle.net/20.500.12386/36878
Journal	EARTH AND PLANETARY SCIENCE LETTERS
Volume	534

An endogenic origin of cerean organics

T.J.Bowling, B.C.Johnson, S.Marchi, , M.C.DeSanctis, J.C.Castillo-Rogez, C.A.Raymond
A Southwest Research Institute, 1050 Walnut Street, Boulder, CO, 80302, USA

B Department of Earth, Atmospheric and Planetary Sciences, Purdue University, West Lafayette, IN, 47907, USA

C Istituto di Astrofisica e Planetologia Spaziali–Istituto Nazionale di Astrofisica, 00133 Roma, Italy

D Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

Abstract

Localized deposits of aliphatic organic-rich material have been found on the surface of dwarf planet Ceres, and based on mineralogical context, it has been suggested that these organics formed within Ceres (De Sanctis et al., 2017). However, no obvious source and exposure mechanism can be inferred from the geological settings of the organic-rich terrains. The alternative hypothesis is that the organics were delivered from an exogenic source via impact (Pieters et al., 2018). We numerically simulate the thermal degradation of aliphatic organics delivered to Ceres during hypervelocity impacts, as well as the thermal degradation and excavation of organics from the subsurface. Our models show that exogenic delivery of aliphatic organics is inefficient, as most of the spectral signature of the organic species would be thermally degraded and diluted by mixing with target material in the ejecta blanket of a given crater. Instead, our models suggest that the formation of Ernutet crater excavated a subsurface reservoir of aliphatic organics from a depth of 3-6 km, bringing it close to the surface, where it could be subsequently exhumed by small craters and landslides, compatible with observations.

1. Introduction

Localized organic-rich regions have been detected on the surface of Ceres by the Visible and Infrared Mapping Spectrometer (VIR) onboard Dawn spacecraft. The presence of organic molecules is unambiguously inferred by a spectral signature between 3.3 and

3.6 μm (De Sanctis et al., 2017). While the exact nature of the organic species is undetermined, they are thought to be of aliphatic structure (De Sanctis et al., 2017; 2018a; 2018b; Kaplan et al., 2018; Vinogradoff et al., 2018). Unequivocal detections of organics on Ceres' surface are largely confined to a single region about 100 km across, within and near Ernutet crater (Pieters et al., 2018), but at least one other small region has been suggested to display aliphatic organics (De Sanctis et al., 2018a,b).

Ernutet is a 53.4 km diameter crater in Ceres' northern hemisphere (Fig. 1), and is

located in a relatively ancient, heavily cratered region of the dwarf planet's surface (Marchi et al., 2016). While the age of the crater's formation is unknown, it has a somewhat fresh rim, so it likely is the youngest large crater formed in this region (De Sanctis et al., 2017). The spectral signature of or

ganics is prominent within the southwest and northwest quadrant of the crater floor and proximal ejecta blanket, and corresponds spatially to an enrichment in magnesium- and calcium-rich carbonates (Fig. 1).

Ceres, being a water ice-rich, geologically active world that may have had (or still has) subsurface liquid briny water, is a potentially viable and relatively accessible astrobiological target for future exploration (Castillo-Rogez et al., 2018). As such, determining the origin of cerean organics is a question of great interest. In addition to Ceres, organics have been detected at the surfaces of other C-type bodies such as 24 Themis (Rivkin and Emery, 2010) and 65 Cybele (Licandro et al., 2011), as well as on Saturn's moons Iapetus, Hyperion and Phoebe (Clark et al., 2005; Dalle Ore et al., 2012; Dalton et al., 2012; and Cruikshank et al., 2014). These bodies and Ceres likely accreted a substantial fraction of their organics from the solar nebula. However, in the case of Ceres, these organics could have been processed in a hydrothermal system, which may have also been conducive to the widespread production of new organics (Marchi et al., 2019).

The first detection of organics near Ernutet crater using Dawn's visible and near infrared imaging spectrometer is limited to a 100-

380 m spatial resolution (De Sanctis et al., 2017). In addition, a more precise localization of organic-rich regions (at 35 m/px) within Ernutet crater has been obtained using visible band ratios from Dawn's multispectral framing camera, allowing for a more nuanced understanding of the organics' geologic context (Pieters et al., 2018). Moreover, VIR data taken at a resolution of less than 100 m has been used to infer organic abundances and association with other mineralogical species (De Sanctis et al., 2018a,b). Pieters et al. (2018) found that the detected organics are largely associated with small, fresh craters, suggesting either relatively recent delivery or relatively recent excavation from the cerean subsurface. As such, two main scenarios by which Ernutet organics could be exposed at the surface are possible:

- Exogenic organics could be delivered via small, organic-rich asteroids or comets. In this scenario, one would expect that the signatures of delivered organics would be evenly distributed across the cerean surface. The organics would need to have been delivered fairly recently (10s-100s Myr) so that their infrared signature would not have been degraded by the effects of radiation and interaction with the solar wind (Marchi et al., 2019).

- A reservoir of endogenic organics could have been excavated from the subsurface. The exposure of this reservoir in the near surface may be related to the formation of Ernutet crater, which may have uplifted deeply seated organics from depth when it formed. The organics within this reservoir could be primordial or produced locally, for instance, within a hydrothermal system (e.g., Schulte and Shock, 2004). Subsequent, small, recent impacts would have exposed the organic-rich material at the surface.

Organic molecules can become unstable at the high temperatures experienced during impacts. When this happens, the carbon-carbon bonds within a given molecule can break, a process we call here 'thermal degradation'. The temperature-induced breaking of C-C bonds leads to the progressive loss of CH₂- and CH₃- groups, which in turn leads to the progressive suppression of the characteristic aliphatic spectral absorption

between 3.3 and 3.6 μm . The kinetics of this process are governed by a temperature dependent Arrhenius type equation described in more detail below (Section 3). Kebukawa et al. (2010) studied how the 3.3-3.6 μm spectral absorption feature decayed with increased temperature for both insoluble organic matter within many meteorites, as well as for bulk samples of the organic-rich meteorite Murchison. They were able to derive the kinetic constants for the suppression of aliphatic spectral absorption, which we employ as an empirical basis for our modeling. While this data is somewhat limited in that it is not specific to shock-induced thermal degradation (experimental data from flyer plate or shock tube experiments would be prefer-

able, but do not exist to our knowledge), it is sufficient to capture the general behavior of cerean-like organics that are exposed to high temperatures.

To better understand if organics can be delivered to the surface of Ceres via impact in such a way that they remain mostly intact and in large enough quantities to be detected, we use numerical models of the impact process coupled with a thermal degradation model describing the breakdown of aliphatic organics and suppression of their spectral signature.

2. Methods

2.1. Impact simulations

To quantify the impact induced thermal decomposition of organics delivered to Ceres, we first model the impact of organic-rich bodies into Ceres using the iSALE-3D shock physics code (Elbeshausen et al., 2009; Elbeshausen and Wünnemann, 2011). This code is based on a hydrodynamic solution scheme described in Hirt et al. (1974). The development history of iSALE-3D is described in Elbeshausen et al. (2009). This code includes a strength model (Collins et al., 2004; Melosh et al., 1992; Ivanov et al., 1997), a porosity compaction model (Wünnemann et al., 2006; Collins et al., 2011), and various equations of states appropriate for geologic materials. Our simulations are run on a three-dimensional half-space Eulerian (fixed cell) computational mesh. The initial target within our simulations is composed of a mixture of serpentine and water ice with a constant temperature of 150 K, reflective of the surface temperature below the skin depth of the cerean surface. Both components of our target mixture have semi-analytic equations of state derived from the code ANEOS for serpentine (Brookshaw, 1998) and H₂O (Turtle and Pierazzo, 2001). The technique used to describe how mixed material equations of state are addressed within our simulations is based on Pierazzo et al. (2005) and is described in detail in Bowling et al. (2019). Construction of the mixed material equation of state assumes mechanical and thermal equilibrium, an assumption that is only valid for an intimate mixture ice and rock with grain sizes small enough that thermal equilibration timescale is shorter than the timescale of shock compression (Ivanov and Pierazzo, 2011). The mass fraction of ice in our simulation targets is a constant 20%, consistent with crustal ice concentrations derived from investigations of Ceres' observed topography (Fu et al., 2017). Ceres' low density and high strength suggests gas hydrates are abundant in Ceres' crust (Fu et al., 2017). However, equations of state for clathrate hydrates are not available. Hence, in our simulation targets we assume serpentine plays the role of the strong phase and assume a constant mass ratio of serpentine to water ice of 4:1 (80% serpentine, 20% water ice). Material strength parameters are the same as those used in Bowling et al. (2019).

To explore the effect of impactor size on organic degradation we vary our impactor diameters from 10 m to 4 km and keep the same model resolution of 40 cells per projectile radius. We test both typical impact velocities appropriate for the asteroid belt of 4.8 km s^{-1} , as well as higher impact velocities expected in a scenario in which Ceres was struck by an organic-rich comet at 10 km s^{-1} . To test the influence of impact angle on thermal degradation of organics, our impact angles vary from 30° to 90° relative to horizontal. Finally, we test impactors composed of both dunite (Benz et al., 1989) (often used to represent asteroidal material), and of 50% porous ice (representative of the density and shock properties of a cometary impactor) (Turtle and Pierazzo, 2001).

2.2. Computing the thermal degradation of aliphatic organics within impactor and target

At the beginning of a given simulation, we place a Lagrangian tracer particle within each computation cell of both the impactor and a region of the target strongly affected by the impact shock wave. These tracer particles follow the flow of material, tracking the evolution of temperature within a given parcel of the impactor or target through time. For each simulation, this evolution is tracked with a temporal resolution of $\Delta t = D/1000U$, where D is the impactor diameter in m, and U is the impactor velocity in ms^{-1} . This is a very high temporal resolution compared to the typical time at which a given parcel of material spends at high temperature and pressures following the passage of an impact induced shockwave (D/U ; Melosh, 1989), but is necessary in order to adequately capture the shock induced thermal degradation of organics within both the impactor and target.

Following the method described in Pierazzo and Chyba (1999), we compute the mass fraction of aliphatic organics that have survived thermal degradation (δ) as follows: The rate of thermal degradation within a given Lagrangian tracer at a given time is computed as a function of temperature as

$$\delta_{\Delta t} = -k\delta(t)\Delta t \quad (1)$$

where

$$k = Ae^{-E_0/RT(t)} \quad (2)$$

is the Arrhenius rate constant, $T(t)$ is the temperature of a given tracer at a given time, $\Delta t = D/1000U$ is the time step duration, $\delta(t)$ is the remaining mass fraction of aliphatic organics within a tracer at a given time (initially $\delta(0) = 1$), E_0 (109 kJ mol^{-1}) and A ($8.7 \times 10^4 \text{ s}^{-1}$) are the experimentally determined activation energy and frequency factor for degradation of aliphatic organics in insoluble organic matter (Kebukawa et al., 2010), and R is the universal gas constant ($8.315 \text{ JK}^{-1}\text{mol}^{-1}$). Note that degradation of aliphatic organics may result in the creation of aromatic organics rather than full degradation (Kebukawa et al., 2010). To avoid repetition, we will refer to aliphatic organics as organics from this point on-ward. Finally, the mass concentration of organics is updated as $\delta(t+\Delta t) = \delta(t) - \delta_{\Delta t}$. For reference to reach a fraction of surviving organics $\delta = 10\%$ material would need to be heated to 800, 1000, or 1200K for 346, 13.1, or 1.47 seconds, respectively. Within this formulation, the mass fraction of surviving organics δ is independent of the initial concentration of organics within the pre-impact impactor or target. To obtain a total concentration of organics β , one can simply multiply δ by the initial

concentration of organics of a given tracer. That is to say, for an impactor of mass M_{impact} initially composed of $\beta=20\%$ organics and a final mass averaged mass fraction of $\delta=10\%$, the total mass of non-thermally degraded organics delivered to Ceres is

$$M = \beta\delta M_{\text{impact}} = 0.02M_{\text{impact}} \quad (3)$$

Reasonable values of β for solar system objects vary widely. A C-type main belt asteroid may have organic concentrations of up to a few weight percent (Alexander et al., 2017), while comets may have considerably higher concentrations of up to 50% (e.g., Bardyn et al., 2017). In either case, if δ is low, then the remaining mass of delivered, non-thermally degraded organics is similarly small. Due to constraints on computational resources, our simulations are terminated at the end of the transient crater growth. As a result, we do not capture the mechanics of how post-impact organics become distributed during crater collapse. This prevents us from describing in detail the final location of non-thermally degraded impactor and target material. In some cases, this material may exceed Ceres' escape velocity making our estimates somewhat conservative. Most of the shock induced thermal degradation of both the impactor and target within our simulations happens quickly, and has largely ceased by the time the transient crater has finished growing. However, degradation may continue after formation of the transient crater making our calculations somewhat conservative.

The experiments of Kebukawa et al. (2010) only went up to temperatures of 573K while much of the material in our simulated impacts reaches temperatures exceeding 1000K. To determine the activation energy and frequency factor, Kebukawa et al. (2010) produced fits to their data assuming a range of kinetic reaction mechanisms. Of their three favored mechanisms, the activation energy and frequency factor from their best fitting mechanism (used here) produces the lowest degradation rate at temperatures exceeding 1000 K. The experiments of Kebukawa et al. (2010) were performed on insoluble organic matter in an inert atmosphere, so there is no external source of oxygen, which could enhance degradation of organics at high temperatures. As previously stated the experiments of Kebukawa et al. (2010) are performed at standard pressure. The high pressures occurring in a shock can enhance organic degradation by lowering activation energies or causing the condensation of carbon into larger, non-aliphatic clusters (Manaa et al., 2009; Koziol and Goldman, 2015). Although our simulations assume asteroid-like impactors are non-porous, many asteroids are rubble piles with up to $\sim 50\%$ porosity (Walsh, 2018). Inclusion of porosity or use of more compressible materials tends to increase post shock temperatures (Melosh, 1989) and would enhance thermal degradation. Thus, our assumptions regarding thermal degradation and survival of exogenic organics are conservative and tend to underestimate the amount of degradation that should occur during an impact.

3. Results

3.1. Survival of exogenic delivered organics

The principal factors controlling the amount of delivered organics that survive a given impact are impactor velocity, impactor size, and impact angle. A more precise and thorough quantification of each of these factors influence is described in detail in the study of Pierazzo and Chyba (1999) which investigated the impact delivery of amino acids to early Earth. Thus, we will only briefly summarize key points in the context of our cerean simulations.

In general, higher impact velocities enhance thermal degradation. This is because higher

velocities result in higher shock temperatures within the impactor, which in turn leads to a corresponding increase in the decay rate k . As such, organics contained within an ‘asteroid-like’ impactor are considerably more likely to survive than in a ‘comet-like’ impactor, as the latter has double the impact velocity, on average, for Ceres. In the case of $D=10$ m, and an impact angle of 45° , the mass averaged surviving fraction of organics is 10% in asteroidal impacts, as opposed to $<1\%$ in cometary impacts (Fig. 2 A vs. C; Fig. 3). Due to the necessarily modest resolution of 3D calculations, volume estimate precisions under 1% should be viewed with caution.

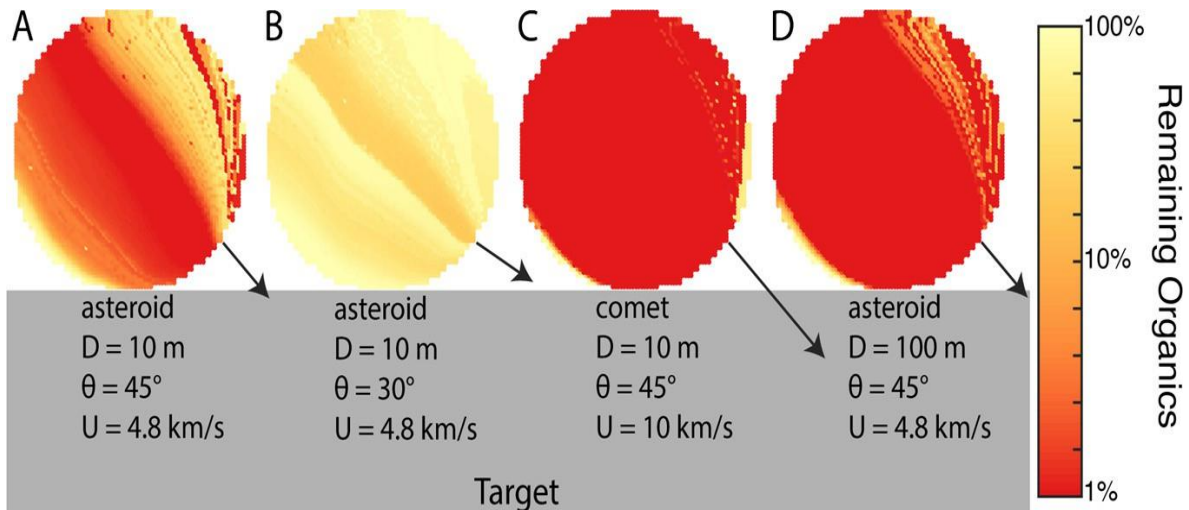


Fig. 2. Provenance plots of impactor organic concentrations following impact delivery to Ceres. This plot shows the degree of thermal degradation experienced by Lagrangian tracer particles initially contained within the impactor, mapped back to their pre-impact location. The tracer particles shown here are from a slice through the center of the impactor. The impactor direction of motion is from top to bottom and from left to right. (A) 45° dunite ‘asteroid-like’ impact, $D=10$ m, $U = 4.8$ km s $^{-1}$. (B) 30° dunite ‘asteroid-like’ impact, $D=10$ m, $U=4.8$ km s $^{-1}$. (C) 45° water ice ‘comet-like’ impact, $D=10$ m, $U = 10$ km s $^{-1}$. (D) 45° dunite ‘asteroid-like’ impact, $D=100$ m, $U = 4.8$ km s $^{-1}$. The highest rate of survival is in scenario B, with a relatively low impact velocity, small diameter, and highly oblique impact angle. Increasing either the impact angle (A), the impact velocity (C), or the impactor size (D) strongly increase the degree of experienced thermal degradation.

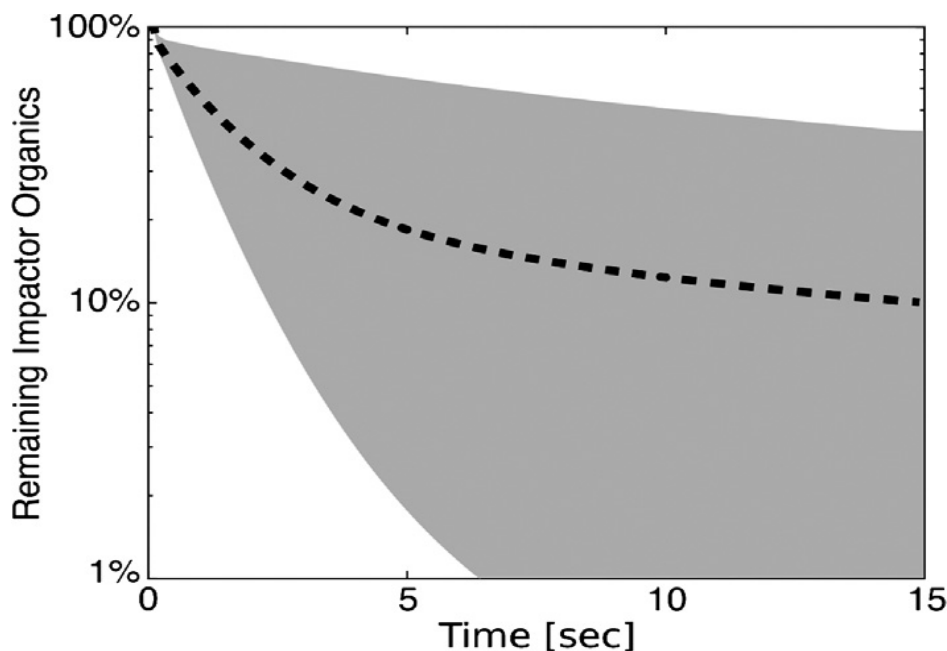


Fig. 3. Time series of thermal degradation within impactors delivered to Ceres. The dashed line shows the mass averaged thermal degradation of organics for all Lagrangian tracer particles originating in the impactor for a 45° dunite ‘asteroid-like’ impact, $D = 10$ m, $U = 4.8$ km s⁻¹ (corresponding to Fig. 2, Panel A). The top of the gray region shows the thermal degradation of a 30° dunite ‘asteroid-like’ impact, $D = 10$ m, $U = 4.8$ km s⁻¹ (Fig. 2, Panel B). The bottom of the gray region shows the thermal degradation of a 45° water ice ‘comet-like’ impact, $D = 10$ m, $U = 10$ km s⁻¹ (Fig. 2, Panel C). For most cases, the rate of thermal degradation has largely dropped off well before the transient crater has finished growing (~ 20 -30 sec).

When an impactor collides with the cerean surface, a shock-wave propagates from the point of impact upwards towards the back of the impactor, heating material to very high temperatures. Material remains at high temperatures until a rarefaction wave propagates downwards from the back of the impactor and into the target. The amount of time (τ) spent at high temperature after the passage of the shock wave, but before the arrival of the rarefaction wave is directly dependent on the size of the impactor, and can be loosely approximated as $\tau = D$ (Melosh, 1989). As such, organic species can survive delivery in dust- to centimeter- scale impactors, but are thoroughly eliminated in meter to kilometer scale impactors, unless they are slow. After release from high pressure, material temperature may still be high enough to cause degradation of organics. We test this dependence on impactor size for cerean impactors by comparing the relative survival rates between $D=10$ m and $D=100$ m impactors (Fig. 2 A vs. D). In the case of $D=10$ m, and an impact angle of 45°, the mass averaged rate of survival is 10%, whereas in the case of the 100 m impactor, the survival rate is a much lower at 1.6%. This means that, unless they are relatively slow, only relatively small impactors may be capable of delivering significant organic signatures to Ceres. Considering this and the lack of evidence that Ernutet was created by a highly oblique impact, it is unlikely that detected organics were delivered by the Ernutet forming impactor ($D=2$ -4 km).

The angle of impact in a given collision also plays an important role in determining the

quantity of organics that are thermally degraded. In general, the lower the impact angle (measured from horizontal), the lower the amount of organic material that is destroyed. This is because impacts at low angles, in bulk, reach lower post-shock temperatures, and spend less time at high temperature

between shock and rarefaction arrivals. For $D=10$ m impactors, the amount of organics destroyed in a 30° impact is ~ 4 times smaller than in a 45° impact (Fig. 2 A, B; Fig. 3). This implies that low angle, relatively small impacts can deliver exogenic organics to the surface of Ceres fairly efficiently. However, such low angle impacts are relatively rare (e.g., the probability of an impact occurring at an angle less than 30° is 25%) (Shoemaker, 1962). Often times to account for the effect of impact angle on shock heating, the vertical component of the impact velocity of a corresponding oblique impact is used as the impact velocity in a vertical impact simulation (Elbeshhausen et al., 2009; Pierazzo and Melosh, 2000). Thus, a lower velocity impact may preserve organics in a similar way to more oblique impacts at higher impact velocities. For example, an impactor striking the target vertically at 2.4 km/s would preserve a similar amount of organics as our 30° impact simulation at 4.8 km/s. By combining the impact velocity probability distribution (Marchi et al., 2016; Hiesinger et al., 2016) with the probability of an impact occurring at a given incidence (Shoemaker, 1962), we find 41% of small impacts ($D=10$ m) occurring on Ceres could preserve at least the same fraction of organics as the simulation with 4.8 km/s impact velocity and 30° impact angle (Fig. 2 B). As discussed above, the fraction of impactor that might preserve organics decreases as impactor size increases.

Of the 41% of the small impacts that may preserve organics, 49% occur at impact angles less than 30° . In an oblique impact more impactor material would be incorporated in distal ejecta rather than being emplaced locally (e.g. Elbeshhausen et al., 2009). So although oblique impacts tend to preserve more organic material (Fig. 2) this material may escape Ceres or be diluted and spread over a larger area than in a vertical impact. Moreover, if small low-angle low-velocity impacts were responsible for delivery of organics, we would expect a high proportion of elliptical craters associated with organic material. We estimate that about 28% of these potentially organic preserving craters should be el-

liptical assuming an onset of elliptical craters at 20° (Elbeshhausen et al., 2013). A high fraction of elliptical craters in the population of small craters associated with cerean organics is not apparent (Pieters et al., 2018).

Studies of impactor survival show that the rear surface of the impactor experiences relatively low shock pressures and heating (Potter and Collins, 2013). One might expect this material has a high organic survival fraction. Organic survival, however depends on the integrated temperature history of the material. For 10 m impactors striking at 4.8 km s⁻¹ the contact and compression timescale is only a few milliseconds and decay of organics occurs on a much longer timescale (Fig. 3). We find that cool material from the back of the projectile is warmed as it spreads out lining the growing transient crater.

This warming of cool material is mainly due to shear heating (Kurosawa and Genda, 2018; Wakita et al., 2019) (Figure S1), but is also accompanied by a similar heating of cool material through numerical diffusion. Although this mixing of hot and cold material and numerical diffusion of heat may be a result of our resolution, such mixing occurs in nature at late times in the cratering process, as evidenced by clastic impact melts and impact breccias. The timescale for material to come to thermal equilibrium depends on the size of the cold clasts though. The region of lightly shocked near surface material is relatively thin for spherical impactors (Potter and Collins, 2013), however, and we expect the uncertainty introduced by numerical diffusion is smaller than uncertainties described previously.

3.2. Survival of endogenic excavated organics

Although organics detected on the cerean surface occur over a wide area, most are localized within the interior and proximal ejecta of Ernutet crater. Because of this, it is possible that the Ernutet impact itself played an important role in allowing organics to be detectably localized on the dwarf planet's surface. In this scenario, the formation of Ernutet crater may have uplifted, and partially exposed a deep, organic-rich reservoir at the cerean surface.

We model the formation of an Ernutet-like cerean crater following the impact of a $D=2.8$ km dunite impactor into an 80% serpentine, 20% water ice target to quantify the amount of thermal degradation experienced by excavated and uplifted target material.

The impactor size is chosen based on the scaling laws of Johnson et al. (2016), and assuming an impact angle of 45° and an impact velocity of 4.8 km s^{-1} . Because we hold this impactor size constant, the final transient diameter changes in our simulations depending on impact angle and only the 45° produces the correct final crater size according to scaling laws.

Fig. 4 shows provenance plots (Lagrangian tracer particles at their pre-impact locations) of the thermal degradation of target material for an Ernutet-like crater following impacts at 90° , 45° , and 30° . In each case, the region immediately below the impact site, where the shock pressures and temperatures are highest, is strongly depleted in organics. This depleted material largely stays within and coats the bottom of the transient crater floor. The gray shaded regions in Fig. 4 show the location of pre-impact material that is ejected beyond the transient crater rim, and the arrows show the direction of motion for that ejection. Our simulations make no assumption about the pre-impact location or presence of endogenic organics, but by analyzing the provenance of ejecta, our simulations provide some constraints on possible depth of origin and degree of degradation of any organics that may have been present in Ceres' interior. The majority of ejected material experiences little to no impact-induced thermal degradation. As such, the Ernutet collision could have excavated a subsurface endogenic reservoir from a pre-impact depth of up to 4.8 km, in the case of a 45° impact, and deposited it on the surface without efficiently destroying the component organic molecules (Fig. 4B).

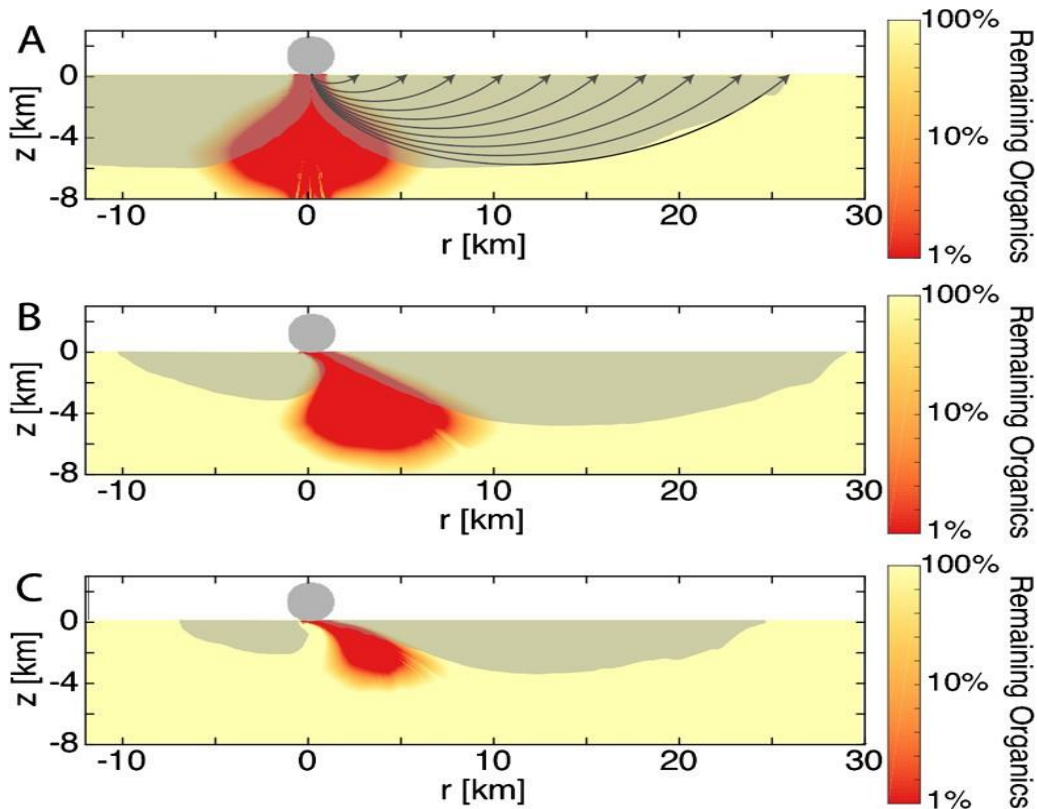


Fig. 4. Provenance plot of impact induced thermal degradation of the cerean subsurface due to the formation of Ernutet crater. The colors in this plot show the degree of thermal degradation experienced in the cerean subsurface following a collision with a $D=2.8$ km diameter impactor moving at 4.8 km s^{-1} and colliding at an impact angle of 90° (A), 45° (B), and 30° (C). Gray regions show material that is excavated upwards and outside of the transient crater rim. In panel A, arrows show streamlines derived from the Maxwell Z model with $Z = 3.1$, and give a sense of flow direction. The bottom most streamline excavates the deepest, and also ejects material at the slowest velocity. This means that the deepest excavated material is largely deposited close to the transient crater rim. Some of this material would then be slumped back into the crater during the collapse process. In the oblique impact scenarios, the excavation flow reaches deeper into the subsurface in the downrange direction than in the uprange direction. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

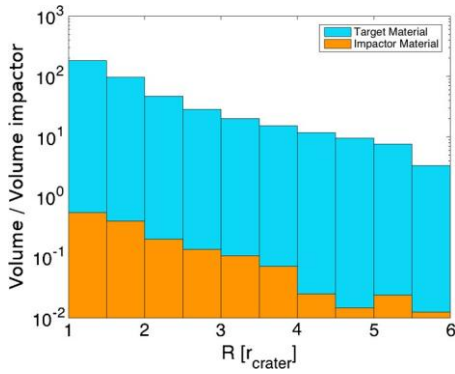


Fig. 5. Volume of impactor and target material within the ejecta of Ernutet crater. The x-axis is the distance from the crater center in units of crater radius, and the y-axis shows the volume of impactor and target material ejected from the crater expressed in units of impactor volume. Bin sizes are 1 crater radius, and account for Lagrangian tracer particles in the downrange quadrant (90 deg aperture) of the transient crater. Note that bins overlap due to the small number of impactor tracers ([1-2], [1.5-2.5], [2-3], [2.5-3.5], etc.). Throughout the ejecta blanket, impactor material is heavily diluted by target material, further reducing the chances of spectrally identifying its organic signature.

4. Discussion

Our simulations of thermal degradation within small impactors suggest that it is unlikely that the organics observed at Ernutet crater were delivered by the Ernutet impactor. First, the mass fraction of organics that would survive when a kilometer sized impactor striking the cerean surface even at a relatively low 30° impact angle would likely be lower than the aliphatic organic fractions inferred of ~4-9% for the organic rich regions of Ernutet crater by VIR (De Sanctis et al., 2017). Secondly, this impactor material would be further mixed with target material within the ejecta blanket. Fig. 5 shows the relative mass fractions of impactor and target material within the downrange ejecta blanket for our 45° Ernutet-forming scenario. In a given portion of the ejecta blanket, the ratio of target to impactor material, by volume, is ~100.

Because the impactor material would likely be turbulently, laterally mixed within the ejecta blanket (Johnson and Melosh, 2014), this would further reduce the concentration and ability to detect exogenically delivered organic material. This mixing would, in effect, add an additional term (γ) to equation (3) to account for the mixing

$$\gamma \beta \delta M_{\text{impact}} = (1\%)(20\%)(10\%) M_{\text{impact}} = 0.0002 M_{\text{impact}}$$

As such, the two effects combined would reduce delivered organics well beyond the orbital detection threshold for any reasonable impact scenario. This mixing result also has implications for other solar system bodies. The origin of dark material on asteroid Vesta has been suggested as contamination by infalling impactors (McCord et al., 2012). Our results suggesting that impactor material is diluted by a factor of 100 within the ejecta blanket of craters suggest that darkening seen on Vesta only requires a very small fraction of impactor material. Alternatively, our assumptions may overestimate the amount of mixing and dilution, or it may be possible that impact delivery resulted in substantial deposition of dark material, later remobilized by subsequent collisions.

Based on our modeling results, we propose that a subsurface layer or region rich in organics and carbonates existed within 5 km of the surface at some point in Ceres' history prior to the formation of Ernutet crater. When Ernutet crater formed, a portion of this reservoir was excavated beyond the transient crater rim, but the organic material contained within was not substantially thermally degraded. During the collapse of the transient crater, a portion of this excavated reservoir was slumped back into the crater, coating a portion of the crater floor. Over time, organics at the very near surface were degraded by exposure to cosmic rays and solar wind (e.g., Marchi et al., 2019), but relatively recent, small craters that form within this now shallow organic reservoir can efficiently further excavate and expose organic-rich material.

It should be noted that in our oblique Ernutet-forming impacts, the depth of excavation is greater in the downrange direction than in the uprange direction (Fig. 5). Because the organics observed within Ernutet crater are largely contained within the southwest quadrant of the crater floor and proximal ejecta blanket, it is possible to further infer that the Ernutet-forming impactor collided with Ceres on a NE to SW trajectory. In this scenario, the excavation flow was only deep enough to reach the subsurface organic-rich reservoir in the downrange direction. For example, if the impact

angle was 45° , and the top of the reservoir lies between 3.5 km and 4.5 km depth, a portion of this reservoir would only be excavated in the downrange direction. In addition, this deeply excavated material would be ejected at relatively low velocities (represented by the bottom-most streamline in Fig. 4A). This could further explain why the Ernutet-related organics are prominently seen in the proximal ejecta from the crater. However, it is impossible to say with any certainty that this is the depth at which the organic-rich reservoir existed in the pre-impact surface. An alternate explanation is that the reservoir varied in depth laterally, and extended closer to the surface or only existed in the SW quadrant of the pre-impact surface.

5. Conclusions

We modeled the thermal degradation of aliphatic organics during impacts on Ceres to understand if the organics detected on the dwarf planet were produced endogenically or delivered from

an exogenic source. Our models demonstrate that exogenic impact delivery is inefficient on Ceres, except for the case of very small ($D < 10$ m) and relatively slow or oblique impacts, with the majority of delivered Murchison-type aliphatic organics being destroyed by thermal degradation following the passage of the impact shock wave through the impactor. Instead, our models suggest that the formation of Ernutet crater excavated and exposed a subsurface organic-rich reservoir from 3-6 km depth, probably following an oblique collision with an asteroid impinging on the surface from the northeast.

Our models imply that the organics detected on Ceres are primordial or formed in situ at some point during the dwarf planet's evolution. The exposure of fresh organics by small impacts likely applies to other planetesimals at which organics have been found, such as Themis (Rivkin and Emery, 2010). Ceres is volatile-rich, with the upper crust being composed of at least 30% and perhaps as much as 60% water in volume, in the form of ice or gas hydrates. It is likely that the subsurface hosted considerable volumes of liquid water in the past (Castillo-Rogez et al., 2018). Our result confirms the long-time expectation that Ceres is a target of astrobiological significance (e.g., Castillo-Rogez and Lunine, 2012). Because it is relatively accessible, in comparison to the icy moons of the giant planets, Ceres is a compelling target for future astrobiological investigations of prebiotic chemistry in the solar system. Better understanding the fate of impactor material is an important endeavor. Future modeling efforts combining impact simulations that cover a larger range of impact conditions with monte carlo accretion models could be used to predict the expected distribution of impactor material and surviving organics. Further laboratory work on the shock processing of organics would improve our confidence in the conclusions presented here and be of broad astrobiological interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Conel Alexander, Gareth Collins, Yvonne Pendleton, B. McKinnon and two anonymous referees for constructive comments that greatly improved this manuscript. We gratefully acknowledge the developers of iSALE-3D, including Dirk Elbeshausen, Kai Wünnemann, Gareth Collins and Tom Davison. In this work we use the `more_materials` branch developed by Dirk Elbeshausen to simulate multiple materials in iSALE-3D which produced similar results to tests using iSALE-2D. This branch is currently only available to iSALE developers. The iSALE code is not open access; it is distributed on a case-by-case basis to academic users in the impact community, strictly for noncommercial use. Scientists interested in using or developing iSALE should see www.isale-code.de for details of how to request access.

Appendix A. Supplementary material

References

- Alexander, C.M.O'D., Cody, G.D., De Gregorio, B.T., Nittler, L.R., Stroud, R.M., 2017. The nature, origin and modification of insoluble organic matter in chondrites, the major source of Earth's C and N. *Chem. Erde* 77, 227–256.
- Bardyn, A., Baklouti, D., Cottin, H., Fray, N., Briois, C., Paquette, J., Stenzel, O., Enggrand, C., Fischer, H., Hornung, K., Isnard, R., Langevin, Y., Lehto, H., Le Roy, L., Ligier, N., Meouane, S., Modica, P., Orthous-Daunay, F-R., Ryno, J., Schulz, R., Silen, J., Thrikell, L., Varmuza, K., Zaprudin, B., Kissel, J., Hilchenback, M., 2017. Carbon-rich dust in comet 67P/Churyumov-Gerasimenko measured by COSIMA/Rosetta. *Mon. Not. R. Astron. Soc.* 469.
- Benz, W., Cameron, A.G.W., Melosh, H.J., 1989. *Icarus* 81, 113.
- Bowling, T.J., Ciesla, F.J., Davison, T.M., Scully, J.E.C., Castillo-Rogez, J.C., Marchi, S., 2019. Post-impact thermal structure and cooling timescales of Occator crater on dwarf planet 1 Ceres. *Icarus* 320, 110–118.
- Brookshaw, L., 1998. An equation of state for serpentine. Tech. Rep. Working Paper Series SC-MC-9813. Faculty of Sciences, University of Southern Queensland.
- Carrozzo, F.G., De Sanctis, M.C., Raponi, A., Ammannito, E., Castillo-Rogez, J., Ehlmann, B.L., Marchi, S., et al., 2018. Nature, formation, and distribution of carbonates on Ceres. *Sci. Adv.* 4, e1701645.
- Castillo-Rogez, J.C., Lunine, J.I., 2012. Small worlds habitability. In: Impey, C., Lunine, J., Funes, J. (Eds.), *Astrobiology: The Next Frontier*. Cambridge University Press. In press.
- Castillo-Rogez, J., Neveu, M., McSween, H.Y., Fu, R.R., Toplis, M.J., Prettyman, T., 2018. Insights into Ceres' evolution from surface composition. *Meteorit. Planet. Sci.* 53, 1820–1843. <https://doi.org/10.1111/maps.13181>.
- Clark, N., et al., 2005. Compositional maps of Saturn's moon Phoebe from imaging spectroscopy. *Nature* 435, 66–69.
- Collins, G., Melosh, H., Wünnemann, K., 2011. Improvements to the epsilon-alpha porous compaction model for simulating impacts into high-porosity solar system objects. *Int. J. Impact Eng.* 38, 434–439.
- Collins, G.S., Melosh, H.J., Ivanov, B.A., 2004. Modeling damage and deformation in impact simulations. *Meteorit. Planet. Sci.* 39, 217–231.
- Cruikshank, D.P., Dalle Ore, C.M., Clark, R.N., Pendleton, Y.J., 2014. Aromatic and aliphatic organic materials on Iapetus: analysis of Cassini VIMS data. *Icarus* 233, 306–315.

Dalle Ore, C.M., Cruikshank, D.P., Clark, R.N., 2012. Infrared spectroscopic characterization of the low-albedo materials on Iapetus. *Icarus* 221, 735–743.

Dalton, J.B., Cruikshank, D.P., Clark, R.N., 2012. Compositional analysis of Hyperion with Cassini VIMS. *Icarus* 220, 752–776.

De Sanctis, M.C., Ammannito, E., McSween, H.Y., et al., 2017. Localized aliphatic organic material on the surface of Ceres. *Science* 355, 719–722. <https://doi.org/10.1126/science.aaj2305>.

De Sanctis, M.C., Ammannito, E., Carrozzo, F.G., Ciarniello, M., Giardino, M., Frigeri, A., Fonte, S., McSween, H.Y., Raponi, A., Tosi, F., Zambon, F., Raymond, C.A., Russell, C.T., 2018a. Ceres's global and localized mineralogical composition determined by Dawn's Visible and Infrared Spectrometer (VIR). *Meteorit. Planet. Sci.*, 1–22.

De Sanctis, M.C., Vinogradoff, V., Raponi, A., Ammannito, E., Ciarniello, M., Carrozzo, F.G., De Angelis, S., Raymond, C.A., Russell, C.T., 2018b. Characteristics of organic matter on Ceres from VIR/Dawn high spatial resolution spectra. *Mon. Not. R. Astron. Soc.* 482, 2407–2421. <https://doi.org/10.1093/mnras/sty2772>.

Elbeshhausen, D., Wünnemann, K., 2011. iSALE-3D: a three-dimensional, multi-material, multi-rheology hydrocode and its applications to large-scale geodynamic processes. In: Schäfer, F., Hiermaier, S. (Eds.), *Proceedings of the 11th Hypervelocity Impact Symposium 2010*. Freiburg, Germany, April 11–15, 2010.

Fraunhofer Verlag, Stuttgart. 828 pp. ISBN 3-8396-0280-7, ISBN 978-3-8396-0280-5, ISSN 1612-6718. *Epsilon. Forschungsergebnisse aus der Kurzzeitchronamik*, 20.

Elbeshhausen, D., Wünnemann, K., Collins, G.S., 2009. Scaling of oblique impacts in frictional targets: implications for crater size and formation mechanisms. *Icarus* 209 (204), 716–731.

Elbeshhausen, D., Wünnemann, K., Collins, G.S., 2013. The transition from circular to elliptical impact craters. *J. Geophys. Res., Planets* 118, 2295–2309. <https://doi.org/10.1002/2013JE004477>.

Fu, R.R., Ermakov, A.I., Marchi, S., Castillo-Rogez, J.C., Raymond, C.A., Hager, B.H., Zuber, M.T., King, S.D., Bland, M.T., De Sanctis, M.C., Preusker, F., Park, R.S., Russell, C.T., 2017. The interior structure of Ceres as revealed by surface topography. *Earth Planet. Sci. Lett.* 476, 152–164.

Hiesinger, H., Marchi, S., Schmedemann, N., Schenk, P., Pasckert, J.H., Neesemann, A., O'Brien, D.P., Kneissl, T., Ermakov, A.I., Fu, R.R., Bland, M.T., Nathues, A., Platz, T., Williams, D.A., Jaumann, R., Castillo-Rogez, J.C., Ruesch, O., Schmidt, B., Park, R.S., Preusker, F., Buczkowski, D.L., Russell, C.T., Raymond, C.A., 2016. Cratering on Ceres: implications for its crust and evolution. *Science* 353, aaf4759. <https://doi.org/10.1126/science.aaf4759>.

Hirt, C.W., Amsden, A.A., Cook, J.L., 1974. An arbitrary Lagrangian-Eulerian computing method for all flow speeds. *J. Comput. Phys.* 14 (3), 227–253.

Ivanov, B.A., Deniem, D., Neukum, G., 1997. Implementation of dynamic strength models into 2D hydrocodes: applications for atmospheric breakup and impact cratering. *Int. J. Impact Eng.* 20, 411–430.

Ivanov, B.A., Pierazzo, E., 2011. Impact cratering in H₂O-bearing targets on Mars: thermal field under craters as starting conditions for hydrothermal activity. *Me-*

teorit. Planet. Sci. 46, 601–619. <https://doi.org/10.1111/j.1945-5100.2011.01177.x>.

Johnson, B.C., Melosh, H.J., 2014. Formation of melt droplets, melt fragments, and accretionary impact lapilli during a hypervelocity impact. *Icarus* 228, 347–363.

Johnson, B.C., et al., 2016. Spherule layers, crater scaling laws, and the population of ancient terrestrial impactors. *Icarus* 271, 350–359.

Kaplan, H.H., Milliken, R.E., Alexander, C.M.O'D., 2018. New constraints on the abundance and composition of organic matter on Ceres. *Geophys. Res. Lett.* 45.

Kebukawa, Y., Nakashima, S., Zolensky, M.E., 2010. Kinetic of organic matter degradation in the Murchison meteorite for the evaluation of parent-body temperature history. *Meteorit. Planet. Sci.* 45 (1), 99–113.

Koziol, L., Goldman, N., 2015. Prebiotic hydrocarbon synthesis in impacting reduced astrophysical icy mixtures. *Astrophys. J.* 803, 91.

Kurosawa, K., Genda, H., 2018. Effects of friction and plastic deformation in shock-comminuted damaged rocks on impact heating. *Geophys. Res. Lett.* 45, 620–626.

Licandro, J., Campins, H., Kelley, M., Hargrove, K., Pinilla-Alonso, N., Cruikshank, D., Rivkin, A.S., Emery, J., 2011. (65) Cybele: detection of small silicate grains, water-ice, and organics. *Astron. Astrophys.* 525, A34.

Manaa, M.R., Reed, E.J., Fried, L.E., Goldman, N., 2009. Nitrogen-rich heterocycles as reactivity retardants in shocked insensitive explosives. *J. Am. Chem. Soc.* 131, 5483–5487.

Marchi, S., Ermakov, A.I., Raymond, C.A., Fu, R.R., O'Brien, D.P., Bland, M.T., Ammannito, E., De Sanctis, M.C., Bowling, T., Schenk, P., Scully, J.E.C., Buczkowski, D.L., Williams, D.A., Hiesinger, H., Russell, C.T., 2016. The missing large impact craters on Ceres. *Nat. Commun.* 7, 12257.

Marchi, S., Raponi, A., Prettyman, T.H., De Sanctis, M.C., Castillo-Rogez, J., Raymond, C.A., Ammannito, E., Bowling, T., Ciarniello, M., Kaplan, H., Palomba, E., Russell, C.T., Vinogradoff, V., Yamashita, N., 2019. An aqueously altered carbon-rich Ceres. *Nat. Astron.* 3, 140–145.

McCord, T.B., Li, J.-Y., Combe, J.-P., McSween, H.Y., Jaumann, R., Reddy, V., Tosi, F., Willaims, D.A., Blewett, D.T., Turrini, D., Palomba, E., Pieters, C.M., De Sanctis, M.C., Ammannito, E., Capria, M.T., Le Corre, L., Longobardo, A., Nathues, A., Mit- tlefehldt, D.W., Schroder, S.E., Hiesinger, H., Beck, A.W., Capaccioni, F., Carsenty, U., Keller, H.U., Denevi, B.W., Sunshine, J.M., Raymond, C.A., Russell, C.T., 2012. Dark material on Vesta from the infall of carbonaceous volatile-rich material. *Nature* 491, 83–86.

- Melosh, H.J., 1989. *Impact Cratering: A Geologic Process*. Oxford Univ. Press, New York.
- Melosh, H.J., Ryan, E.V., Asphaug, E., 1992. Dynamic fragmentation in impacts: hydrocode simulation of laboratory impacts. *J. Geophys. Res.* 97, 14,735–14,795.
- Pierazzo, E., Artemieva, N.A., Ivanoc, B.A., 2005. Starting conditions for hydrothermal systems underneath Martian craters: hydrocode modeling. *Geol. Soc. Am. Spec. Pap.* 384, 443–457.
- Pierazzo, E., Chyba, C.F., 1999. Amino acid survival in large cometary impacts. *Meteorit. Planet. Sci.* 34, 909–918.
- Pierazzo, E., Melosh, H.J., 2000. Melt production in oblique impacts. *Icarus* 145, 252–261.
- Pieters, C.M., Nathues, A., Thangjam, G., Hoffmann, M., Platz, T., De Sanctis, M.C., Ammannito, E., Tosi, F., Zambon, F., Pasckert, J.H., Hiesinger, H., Schroder, S.E., Jaumann, R., Matz, K.-D., Castillo-Rogez, J.C., Ruesch, O., McFadden, L.A., O'Brien, D.P., Sykes, M., Raymond, C.A., Russell, C.T., 2018. Geologic constraints on the origin of red organic-rich material on Ceres. *Meteorit. Planet. Sci.*, 1–16.
- Potter, R.W.K., Collins, G.S., 2013. Numerical modeling of asteroid survivability and possible scenarios for the Morokweng crater-forming impact. *Meteorit. Planet. Sci.* 48, 744–757.
- Rivkin, A.S., Emery, J.P., 2010. Detection of ice and organics on an asteroidal surface. *Nature* 464, 1322–1323.
- Schulte, Mitch, Shock, Everett, 2004. Coupled organic synthesis and mineral alteration on meteorite parent bodies. *Meteorit. Planet. Sci.* 39 (9), 1577–1590.
- Shoemaker, E., 1962. In: Kopal, A. (Ed.), *Physics and Astronomy of the Moon*. Academic Press, pp. 283–571.
- Turtle, E.P., Pierazzo, E., 2001. Thickness of a European ice shell from impact crater simulations. *Science* 294 (5545), 1326–1328. <https://doi.org/10.1126/science.1062492>.
- Vinogradoff, V., De Sanctis, M.C., De Angelis, S., Raponi, A., Ferrari, M., Ciarniello, M., Ammannito, E., Russell, C.T., Raymond, C.A., 2018. The nature and evolution of organic matter in Ceres. In: *LPSC*, vol. 49, p. 1419.
- Wakita, S., Genda, H., Kurosawa, K., Davison, T.M., 2019. Enhancement of impact heating in pressure-strengthened rocks in oblique impacts. *Geophys. Res. Lett.* <https://doi.org/10.1029/2019GL085174>.
- Walsh, K.J., 2018. Rubble pile asteroids. *Annu. Rev. Astron. Astrophys.* 56, 593–624. <https://doi.org/10.1146/annurev-astro-081817-052013>.
- Wünnemann, K., Collins, G., Melosh, H., 2006. A strain-based porosity model for use in hydrocode simulations of impacts and implications for transient crater growth in porous targets. *Icarus* 180, 514–527.