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## **Mechanical Properties of the Rocky Interiors of Icy Moons**

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### Key points:

1. We established the failure envelope of chondritic materials under conditions relevant to the rocky interiors of small icy moons
2. Chondritic material has a yield cap around 50 MPa confining pressure, above which its porosity is very small
3. Pressurization and deformation of chondritic material creates energetic cracks, which could contribute to heat dissipation

16

**17 Abstract**

18 Icy moons in the outer Solar System contain rocky, chondritic interiors, but this material is rarely studied  
19 under confining pressure. The contribution of rocky interiors to deformation and heat generation is  
20 therefore poorly constrained. We deformed LL6 chondrites at confining pressures  $\leq 100$  MPa and  
21 quasistatic strain rates, and recorded acoustic emissions (AEs) using ultrasound probes. We defined a  
22 failure envelope, measured ultrasonic velocities, and retrieved elastic moduli for the experimental  
23 conditions. Chondritic material stiffened with increasing confining pressure, and reached its peak  
24 strength at 50 MPa confining pressure. Microcracking events occurred at low stresses, during nominally  
25 “elastic” deformation, indicating that dissipative processes are possible in rocky interiors. These events  
26 were most energetic at lower differential stresses, and occurred more frequently at lower confining  
27 pressures. We suggest that chondritic interiors of icy moons are therefore stronger, less compliant, and  
28 less dissipative with increasing pressure and size.

29

**30 Plain language summary**

31 Many icy moons in the outer Solar System have warm, active interiors, but the source of the heat that  
32 maintains this activity is sometimes unknown. Many of these moons contain rocky layers which are made  
33 of the same material as meteorites that have landed on the Earth. However, we have never previously  
34 studied how this material deforms under confining pressures like those found within icy moons. We  
35 conducted a lab study of the deformation mechanisms of meteoritic material to study how the deformation  
36 response applies to the interior of icy moons. We also analyzed cracking in response to small stress  
37 changes, which occurred at all stages of deformation. We found that the material behaved differently at  
38 low and high confining pressures, with a peak strength at  $\sim 50$  MPa. This indicates that icy moons with  
39 smaller oceans and thinner crusts may deform differently than larger icy moons, and can receive some of  
40 the heat needed to maintain their oceans through cracking processes in their porous cores.

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**44 1. Introduction**

45 Icy moons in the outer Solar System are considered excellent candidate bodies for hosting extraterrestrial  
46 life. The interior properties of these moons are important for determining the feasibility of life, lander  
47 missions, and future priorities in exploring the outer Solar System. The mechanical properties of the cores  
48 of these moons are relatively less well-studied than the properties of their icy crusts and water oceans, as  
49 the cores are likely less dissipative than the ice or liquid layers (e.g., Tobie et al., 2005). The deformation  
50 mechanisms of core material are thus presently still unknown, leaving large uncertainties as to how  
51 dissipation proceeds throughout the entire body: there is an order-of-magnitude difference in potential  
52 heat release from Enceladus’ core, for example, depending on if it is stiff and elastic or if it is highly  
53 deformable and (poro)viscoelastic (Aygün and Čadek, 2022; Rovira-Navarro et al., 2022).

54 The yield strength of a material, which modelers use to predict how a body responds to stress, is  
55 almost always pressure-dependent, and often strain-rate dependent (Mair et al., 2002; Mulliken and  
56 Boyce, 2006). Rocky components of icy moons are frequently chondritic in nature (Kuskov and Kronrod,  
57 2005; Néri et al., 2020; Neumann and Kruse, 2019), and most strength tests of meteoritic material are  
58 conducted at asteroidal conditions: no confinement, and fast strain rates.

59 Confining pressures at the core-ocean or core-mantle boundary of icy moons frequently reach tens of  
60 MPa and more (Neveu et al., 2015; Styczinski et al., 2022; Vance et al., 2018). Almost all tests on  
61 meteoritic material occur at room pressure (Pohl and Britt, 2020). The few tests that do assess strength  
62 and deformation mechanisms of chondritic material under pressure (Ramesh et al., 2017; Voropaev et al.,  
63 2017) do not report strength at pressures relevant to rocky interiors of icy moons. Voropaev et al. (2020)  
64 did study a single sample at confining pressure of 50 MPa, but did not apply any differential stress and  
65 therefore could not measure the strength of the material. Dynamic (fast) deformation experiments  
66 simulating crater formation and impacts on chondrites are also common. These experiments are not easily  
67 applied to planetary strain rates, and there is a larger rate sensitivity in unconfined meteoritic material  
68 than in terrestrial rocks (Kimberley and Ramesh, 2011). Hogan et al. (2015) used Brazilian disk tests in a  
69 Kolsky bar apparatus under confined planar configuration at dynamic strain rates of  $10^1 - 10^3 \text{ s}^{-1}$ , which  
70 yielded a higher peak strength ( $\sim 300$  MPa) than the unconfined tests at similar strain rates, but did not  
71 record enough data at low strain rates to establish a definite change in peak strength for quasistatic tests  
72 conducted at no confining pressure vs. those conducted under confinement.

73 Here, we report the mechanical properties of deforming chondritic material under confining pressure.  
74 These measurements represent the first experimental investigation of chondritic material deformation  
75 under confining pressure similar to that found inside an icy moon. We used fallen meteoritic material,  
76 which is inherently pre-deformed and high-strength. These fallen meteorites are analogs for the rocky  
77 cores and mantles of moons, which have survived accretion and continuous tidal deformation for billions  
78 of years (Nimmo and Pappalardo, 2016).

79 In addition to the bulk mechanical response to deformation, we also studied microcracking behavior as  
80 the rocks were pressurized, and subsequently deformed at elevated confining pressures. Cracks associated  
81 with damage emit dynamic stress waves, observable as acoustic emissions (AEs) with characteristic  
82 frequencies depending on the source characteristics of deformation (Eitzen and Wadley, 1984; Ghaffari et  
83 al., 2014; Lei and Ma, 2014; Li et al., 2021; O’Ghaffari et al., 2023). The internal structure can also be  
84 sampled using throughgoing waves, which acquire signatures of the microstructure as they propagate  
85 through and interact with the material. We used ultrasonic probes in passive and active modes to measure  
86 1) energy release associated with acoustic emissions, and 2) variations of sound velocities and their  
87 transmissivity in the samples under confining pressure. As macroscale behavior arises from microscale  
88 effects, data from all scales is needed to produce a robust picture of deformation dynamics.

89 This paper presents mechanical results from deformation tests, followed by observations of internal  
90 structure based on acoustic emissions and ultrasonic pulsing. We show that as the meteoritic material  
91 encounters higher confining pressures up to 50 MPa, the samples become stronger and emitted high-energy  
92 acoustic waves. Above 50 MPa confining pressure, the material became weaker, and dissipated less energy  
93 via AEs. Our observations indicate that the mechanisms of deformation are controlled by porosity closure,  
94 and that the dissipation of stored energy via microcracking is more pronounced at lower confining  
95 pressures.

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97 **2. Methods**

98 These tests were conducted on samples from the Kilabo meteorite, an LL6 chondrite. Moons have  
 99 broadly chondritic silicate interiors: Néri et al. (2020) suggest that the cores of Titan and Ganymede (and  
 100 possibly Callisto) are carbonaceous chondrites, while Kuskov and Kronrod (2005) infer an low metallicity  
 101 and/or low iron (L/LL) composition for the interior of Europa (and, again, possibly Callisto), and  
 102 Neumann and Kruse (2019) find an ordinary chondritic (OC) composition (likely L/LL) for the rocky  
 103 core of Enceladus. Previous experiments suggest that strength differences between carbonaceous and  
 104 ordinary chondrites are related to the higher porosity of carbonaceous chondrites rather than any inherent  
 105 difference in the material (Flynn et al., 2018; Pohl and Britt, 2020).

106 The meteoritic material was impregnated in epoxy before being drilled into 6.25 mm diameter cores for  
 107 laboratory deformation. The samples were jacketed in soft PVC tubing, then encased in Teflon heat  
 108 shrink tubing prior to deformation (Supplementary material). This material has ~15% microporosity and a  
 109 mean density of ~2.5 g/cm<sup>3</sup>. However, these (and other) properties are heterogeneously distributed  
 110 throughout the sample. Samples were taken from the interior of the meteorite, and there is no alteration  
 111 crust present. Deformation was performed in a Paterson gas medium deformation apparatus (Paterson,  
 112 1990) housed in the Rock Mechanics Laboratory at MIT. A summary of the experimental parameters can  
 113 be found in Supplemental Table 1, and a setup schematic can be found in Figure S1.

114 We applied isostatic confining pressures ( $\sigma_3$ ) of up to 100 MPa, and deformed the samples at room  
 115 temperature (296 K) and constant strain rates of  $10^{-5} \text{ s}^{-1}$ , resulting in triaxial stress ( $\sigma_1 > \sigma_3 =$   
 116  $\sigma_2$ ). Differential stress ( $|\sigma_1 - \sigma_3|$ ) continued to increase until failure, the point at which the samples no  
 117 longer supported increasing stress and began to weaken (Figure 2a).

118 A custom data acquisition system (DAQ) was used in order to record passive AEs and pass active  
 119 ultrasonic waves through the samples. Miniature piezoelectric sensors with a diameter of 1.5 mm were  
 120 created by cementing a piezo-element (0.5 mm tall) within a metallic tube. The piezo-element was then  
 121 coated with gold, to achieve high electrical conductivity. These sensors were attached to microsprings and  
 122 threaded through pistons to allow constant coupling between the sensor and the sample during  
 123 deformation. Signals were amplified at ~60 dB and recorded at 50 MS/s rate with 12 bit resolution using a  
 124 digital oscilloscope (TiePie HS4-50). The majority of amplified signals fell in the frequency range of  
 125 ~50 kHz to 2 MHz. One of the sensors was set to pulse P-waves (Y-cut LiNbO<sub>3</sub>), and the other one  
 126 could receive both P and S waves (X-cut).

127 Microcracking occurred during both pressurization and deformation, releasing strain energy and causing  
 128 vibrations within the sample. The received signals are recorded as displacements at the end of the sample,  
 129 representing a convolution of three main controlling parameters of wave propagation: source  
 130 characteristics, the medium through which waves travel, and the sensor response. We took Fourier  
 131 Transforms of the displacements  $u$  at times  $t$  into corresponding frequencies  $\omega$ , such that  $u(\omega) =$   
 132  $\sum_t u(t)e^{-i\omega t}$ , with amplitudes  $\psi_\alpha = \{u(\omega_\alpha)\}$  over frequency levels  $\alpha$ . This expansion yields  
 133 modulations to the energy state with amplitudes  $C_\alpha$  and eigenvectors  $\phi_\alpha$ , which we use to characterize the  
 134 state of the system  $\vec{\psi}$  such that

$$135 \vec{\psi}(t) = \sum_\alpha C_\alpha e^{-i\omega_\alpha t} \vec{\phi}_\alpha.$$

136

137 For each acoustic emission, we smoothed over the raw emitted waveform with a window of 5 count  
138 intervals (0.1  $\mu$ s), and denoised using wavelet decomposition. From this data, we computed a spectrogram  
139 using the window function  $W$  and time index  $\tau$  to yield power  $P$ , such that

$$140 \quad P(\tau, \omega) = \sum_t W(t - \tau) \psi(t) e^{-i\omega t} .$$

141 We integrated over the duration and frequency range of each event to compute the total power, then  
142 normalized by the mean power of background noise during each test. The power is a direct indication of  
143 how much energy was dissipated due to AEs. We present this quantity as a scalar value relative to the  
144 noise threshold, and discarded any events with a power-to-noise ratio below 1.5.

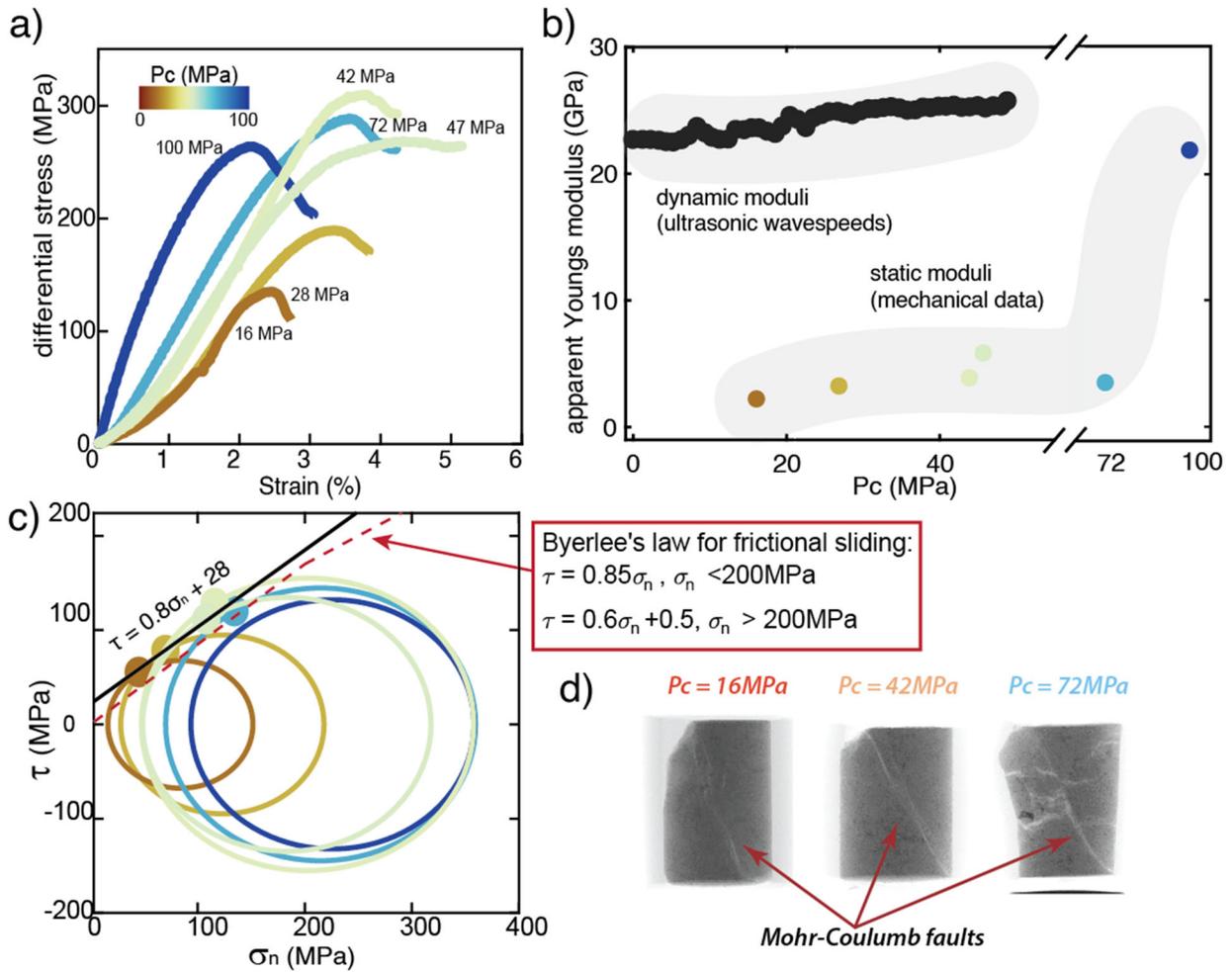
145 See Supplementary Information (figures S2, S3) for more details on acoustic emission data calibration  
146 and acquisition. A comprehensive proof of this integration can also be found in the discussion of the P-  
147 parameter by Ghaffari et al. (2021).

148 After deformation, entire samples were imaged with the table-top micro-computed tomography (micro-  
149 CT) Skyscan system at Woods Hole Oceanographic Institution, using 5-hour scan times at a 4  $\mu$ m pixel  
150 size under 100 kV acceleration voltage.

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155 Figure 1: Mechanical results from deformation tests, represented as a) stress/strain curves, colored by  
 156 confining pressure, b) observed Young's moduli from ultrasonic and mechanical data, c) Mohr circles,  
 157 with a tangent line indicating the Mohr-Coulomb failure envelope, large dots represent fault orientation  
 158 developed at failure and d) CT images of deformed samples, with final faults from peak stress indicated.

159 **3. Results**

160 **3.1. Mechanical data**

161 The peak strength of the samples generally increased with confining pressure before reaching a  
 162 maximum at ~50 MPa Pc (Figure 1a). Above ~50 MPa confining pressure, peak strength decreased with  
 163 increasing confining pressure. The  $\sigma_1$  did not exceed ~350 MPa in any experiment, and so increases in  
 164 confining pressure above 50 MPa lead to decreases in differential stress (Figure 1c). In all cases, the strain  
 165 at peak strength at the point of failure remained close to 3%.

166 The failure envelopes of the experimentally deformed samples are represented as Mohr circles in Figure  
 167 2c. These Mohr circles are a graphical representation of the stress state within a rock at the point of  
 168 failure, plotted in normal stress ( $\sigma_n$ ) vs. shear stress ( $\tau$ ) space such that

$$169 \quad \sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\theta ; \tau = \frac{\sigma_1 - \sigma_3}{2} \sin 2\theta ,$$

170

171 where  $\theta$  is the orientation of the normal to the fault plane with respect to  $\sigma_1$ . The Mohr-Coulomb failure  
172 envelope tangent to the circles indicates the stress conditions expected at failure:

$$173 \quad \tau = 0.8\sigma_n + 28 \text{ (units in MPa).}$$

174 This linear failure envelope is valid only for samples deformed below  $\sim 50$  MPa Pc. Byerlee's Law, which  
175 defines the shear stress needed to slide rocks along a pre-existing fault surface, falls below the range of  
176 stress states recorded during deformation tests, as expected for the deformation of intact rocks. Notably,  
177 no test was able to reach  $\sigma_1$  greater than 350 MPa; the three highest-pressure tests all failed at this point.

178 During several tests of up to 50 MPa confining pressure, we monitored sound velocities using the  
179 piezoelectric sensors placed above and below the sample (See Supplementary Table 1). From these  
180 measurements, we characterized dynamic (unrelaxed) Youngs moduli via p- and s-wave arrival times,

$$181 \quad E_{dyn} = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2}.$$

182 We compared the unrelaxed, microscale  $E_{dyn}$  with the observed macroscale Youngs modulus derived from  
183 mechanical data on stress,  $\sigma$ , and strain,  $\epsilon$ , such that

$$184 \quad E_{qs} = \frac{\sigma}{\epsilon}.$$

185 As materials are stiffer at higher frequencies and shorter length scales (Jackson, 2015), the calculated  
186 Youngs modulus is higher during dynamic probing than during quasistatic bulk deformation (Figure 1b).

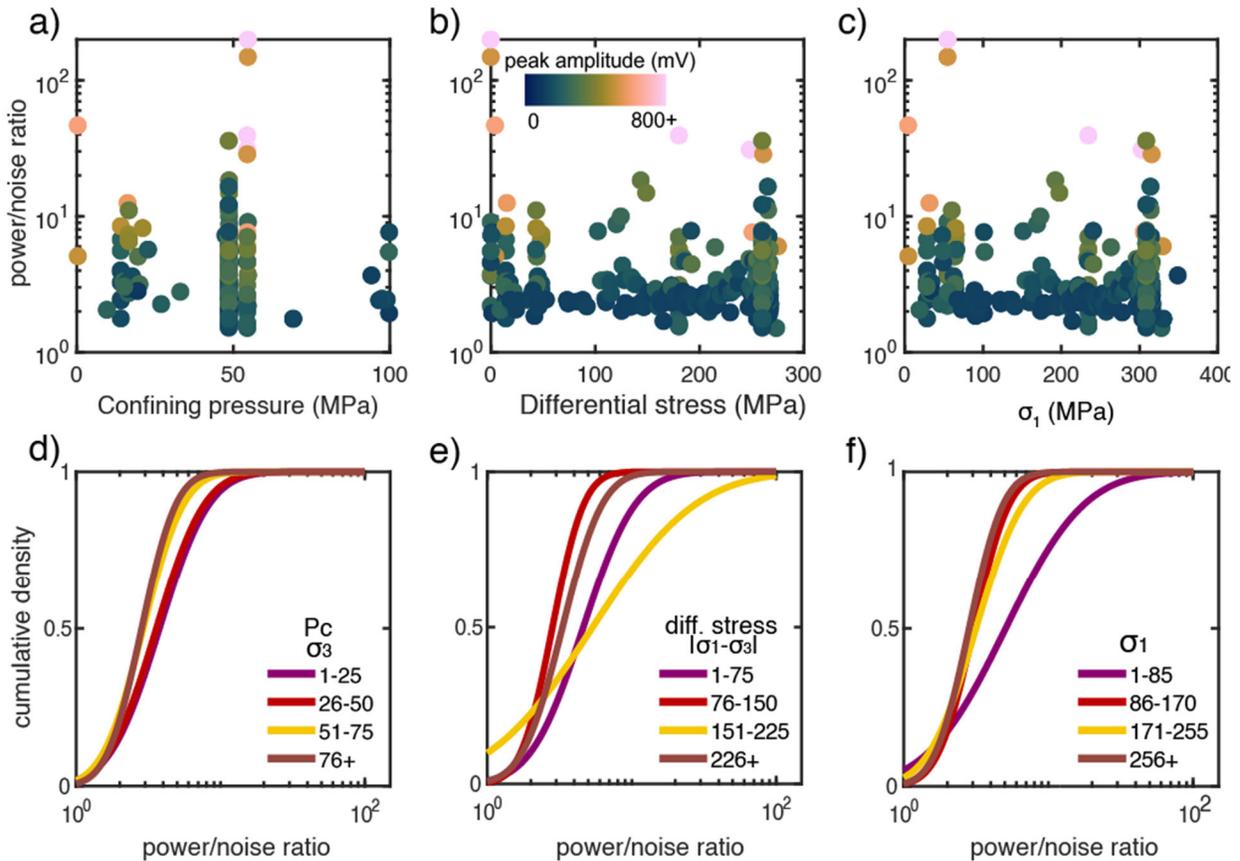
## 187 **3.2. Ultrasonic probes**

### 188 **3.2.1. Acoustic emissions**

189 All samples released energy via microcracking, both during pressurization and deformation.  
190 Microcracking occurred at all sampled pressures (Figure 2a, 2d). The integrated power and maximum  
191 amplitudes of each AEs decreased slightly with increasing differential stress ( $|\sigma_1 - \sigma_3|$ ) (Figure 2b, 2e),  
192 and the power-to-noise ratio was largest for low values of  $\sigma_1$  (Figure 2c, 2f). Many of these energetically  
193 dissipative events occurred during the nominally "elastic" deformation period, when differential stress is  
194 low and no energy release is expected. The material also emitted energy through microcracking during  
195 isotropic pressurization cycles (Figure 3d), when differential stress is zero.

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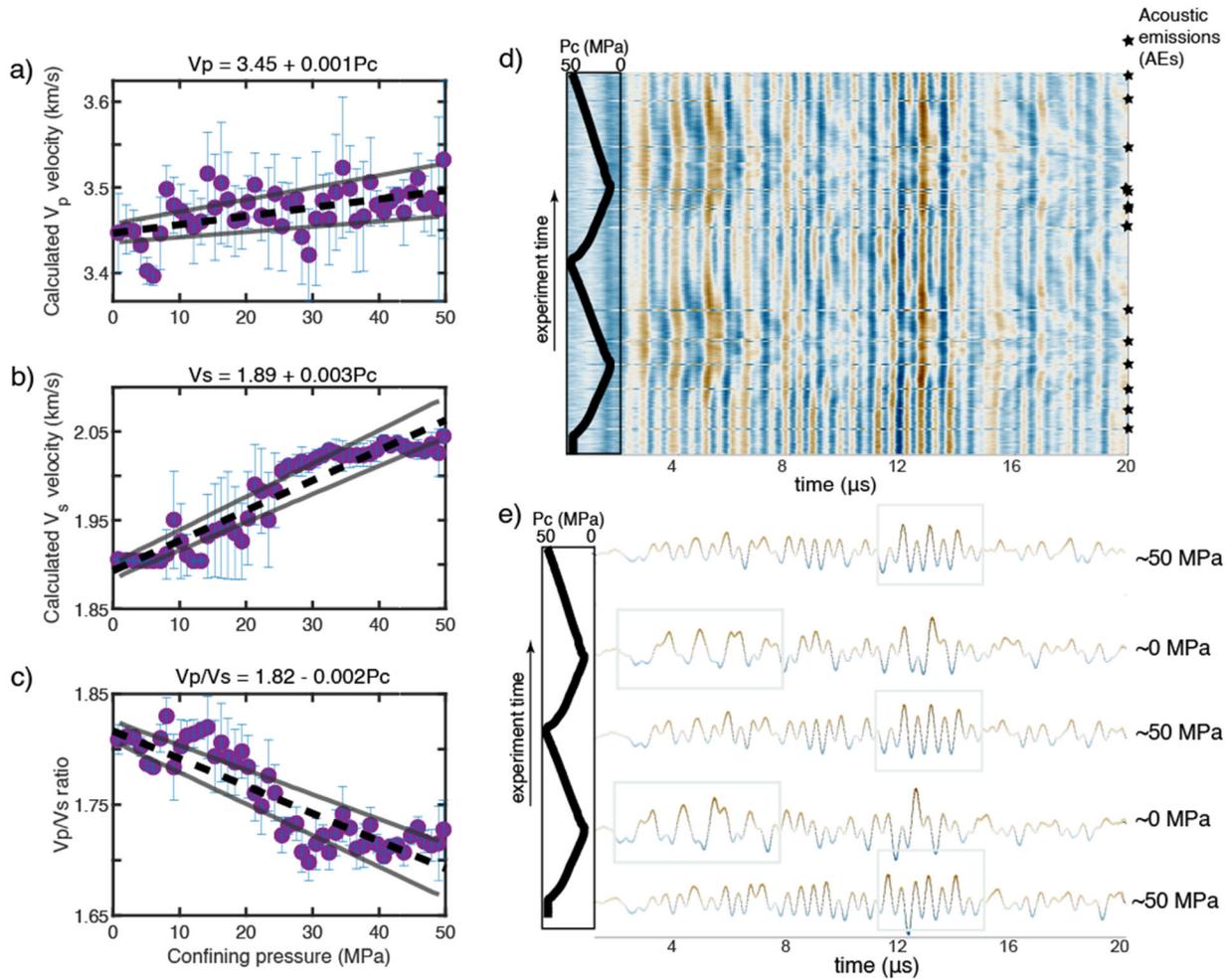
199 Figure 2: (a-c) Power of AEs, normalized by noise threshold for each test, as a function of a) confining  
 200 pressure, b) differential stress, c)  $\sigma_1$ . Each point represents one AE event, and is colored by the maximum  
 201 amplitude of that event following the colorbar in panel b). (d-f) Lognormal cumulative distribution  
 202 functions of total power per event, evolving as a function of d) confining pressure, e) differential stress,  
 203 and f)  $\sigma_1$ . Colored lines correspond to specific stress ranges, in MPa, which are defined specifically for  
 204 each panel in its interior legend.

205

### 3.2.2. Ultrasonic pulsing

206 To determine wavespeeds as a function of pressure, we sent ultrasonic pulses through a sample  
 207 while cycling confining pressure between 0 and 50 MPa, (Figure 3a, 3b, 3c). This procedure allowed us to  
 208 examine if pressure oscillations changed the internal structure of our material and validate our results. We  
 209 examined the entire waveform to see how the structure is affecting throughgoing waves (Figure 3d, 3e).  
 210 The amplitudes and arrival times of throughgoing waves mimicked the pressure conditions, such that at  
 211 lower pressures, comparable parts of the waveform arrived later, and at higher pressures, they arrived  
 212 earlier (Figure 3d). The waveforms also remained similar at the same pressure even after a  
 213 pressurization-depressurization cycle and associated AEs (Figure 3e; S5), suggesting that the  
 214 modifications to internal structure of the material occur on smaller length scales than sampled by  
 215 ultrasonic waves and therefore would not be visible to seismic waves, regardless of the pressure history.

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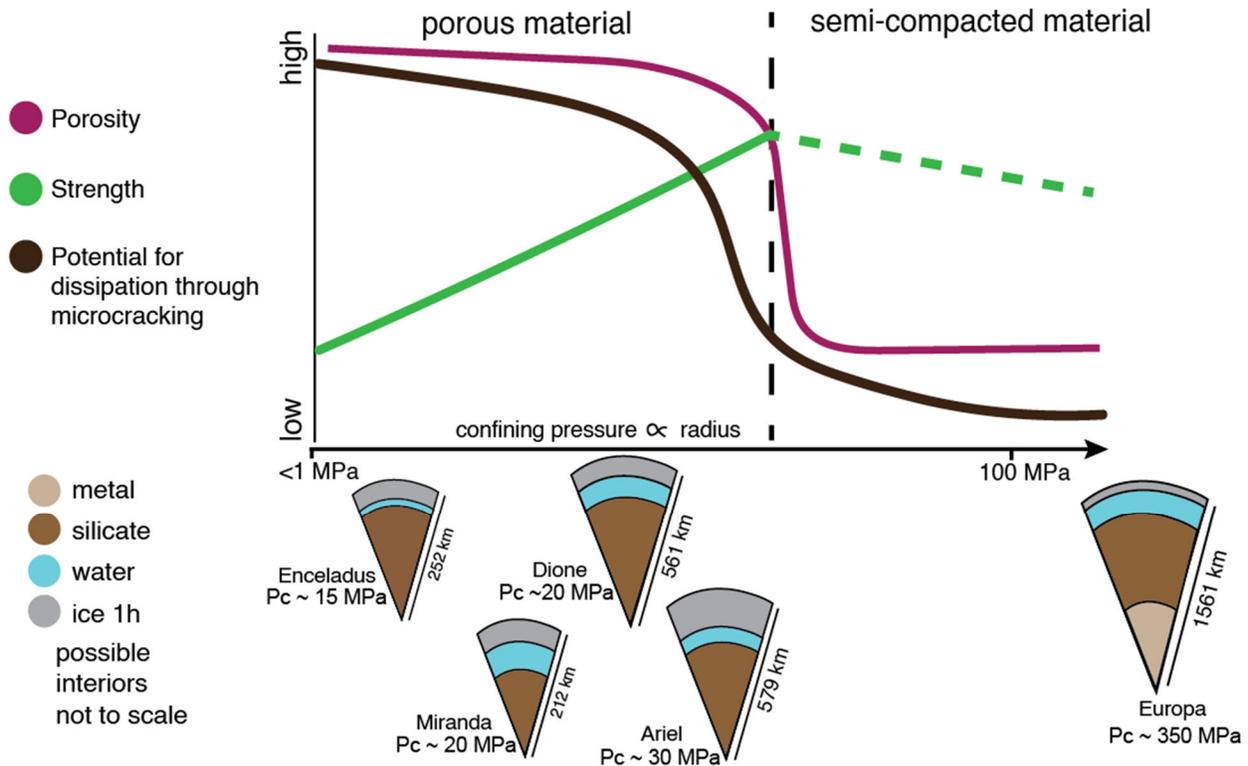
218 Figure 3: Results from ultrasonic pulsing during confining pressure oscillation. a)  $V_p$  wavespeeds. b)  $V_s$   
 219 wavespeeds. c)  $V_p/V_s$  ratio. For a-c, linear trendlines are shown in black, with grey lines denoting 90%  
 220 confidence interval. d) Two full depressurization-repressurization cycles and resultant waveforms. Black  
 221 line indicates pressure conditions. Waveforms are stacked with increasing experimental time, and color  
 222 corresponds with amplitude over wavelength time, from blue (high negative amplitude) to brown (high  
 223 positive amplitude). Horizontal, discontinuous lines marked with stars are energetic acoustic emission  
 224 events, which are separate from the pulsed ultrasonic waves shown here. e) Sample waveforms from 0  
 225 and 50 MPa confining pressure at each inflection point in the cycle. Similar parts of the waveform at 0  
 226 and 50 MPa are highlighted in light grey boxes. See Supplementary Information for further discussion of  
 227 waveform analysis (S4-6).

228

229 **4. Discussion**

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233 Figure 4: A conceptual diagram showing the effects of confining pressure on porosity, strength, and the  
 234 power released via microcracking. Sample interior models for small icy moons are shown in order of  
 235 increasing  $P_c$  at the ocean-rock interface, based on estimates from PlanetProfile by Vance et al (2018).

236 The above results show that the mechanical and acoustic properties of chondritic material, and therefore  
 237 the cores of icy moons, are dependent on confining pressure. Several of these relationships are depicted  
 238 schematically in Figure 4.

#### 239 4.1. Discussion of mechanical data

240 Chondritic material initially strengthens with increasing confining pressure, then undergoes a drop in peak  
 241 differential stress above confining pressures  $>50$  MPa (Figure 1a, 1c). This behavior is similar to the “cap  
 242 model” for compaction and deformation of porous Earth materials. In the cap model porosity drops  
 243 steadily with increasing pressure before dropping rapidly at a point of compactive yield ( $C^*$ ), where the  
 244 load-bearing framework collapses and above which cataclastic flow takes over as the primary mode of  
 245 deformation (Wong and Baud, 2012).

246 Pore closure may therefore proceed in a predictable, yet discontinuous manner across icy moon  
 247 environments. The maximum pressure at which porosity is maintained within a rocky interior should  
 248 decrease with increasing  $P_c$ , then suddenly drop, rather than a slow closure similar to that within the outer  
 249 layers of rocky planets as is often assumed in planetary models (e.g. Vance et al., 2018). The pores do not  
 250 close entirely at this point, but most porosity is lost. It is possible that the maximum normal stress seen in  
 251 our test, 350 MPa, represents the condition for total pore closure. Assumptions of density and  
 252 permeability within cores should see a similar jump. These observations indicate that the mechanisms of

253 deformation may be different in larger moons than in smaller moons, due to the increased confining  
254 pressures from increased overburden at the rock-ocean or rock-ice interface. In bodies where rocky  
255 interiors are under higher confining pressures, pore closure effects may not be as important and material  
256 may be stiffer; in lower-pressure environments, material may deform more easily.

257 Viscoelastic deformation of silicate interiors has been suggested as a mechanism for heat generation and  
258 tidal dissipation in Enceladus and Europa (Kang et al., 2020; Liao et al., 2020; Rovira-Navarro et al.,  
259 2022), but a true viscous response is unlikely in a cold, chondritic layer. Silicates typically require  
260 elevated pressures and temperatures for viscous deformation (e.g. Kohlstedt and Hansen, 2015). Brittle  
261 creep, a mechanism that is active in silicate rocks at low pressures and temperatures (Bernabé and Peč,  
262 2022; Brantut et al., 2013) may generate an additional apparent viscous response, contributing to the total  
263 heat dissipation via microcracking. Similar effects may arise from pore closure and reopening. While not  
264 truly a viscous response, the presence of brittle creep could serve as a nonlinear viscous element over  
265 short timescales and thus should be considered in models for viscoelastic core deformation.

266

#### 267 **4.2. Discussion of acoustic and ultrasonic data**

268 Dissipative acoustic emissions from microcracking events occurred at all pressures sampled, even  
269 at low differential stresses, indicating that even small changes to local stresses can initiate cracks (Figure  
270 2). The  $V_p/V_s$  ratio also decreased with increasing confining pressure (Figure 3c), which occurs as  
271 damage increases (Wang et al., 2012). We suggest that microcracking could be continuously occurring in  
272 rocky interiors of icy satellites, where deviatoric stresses can be on the order of 1 MPa or higher,  
273 changing periodically with the orbit of the satellite (Gao and Stevenson, 2013; McKinnon, 2013). As  
274 these cracks occurred during the nominally elastic component of deformation (low differential stress, low  
275 strain; see Figure 2b, 2e), we suggest that that the energy from these microscale plastic mechanisms  
276 should be associated with the apparent viscous response necessary for dissipation in the silicate core.

277 Moons with thinner crusts and oceans could receive proportionally more heat over their lifetimes  
278 from the deformation of their rocky interiors than larger moons, as their cores will be more deformable at  
279 low pressures and therefore able to dissipate heat during viscoelastic deformation. Local values of  $\sigma_1$  will  
280 be lower in smaller moons as well, corresponding to the most energetic cracking events seen in our tests  
281 (Figure 2c, 2f). As this energy is released, it could contribute to processes such as ice overturn, ocean  
282 maintenance, and possibly even geyser activity as seen on Enceladus' south pole. Pore fluids change the  
283 local stress state by lowering the effective pressure, so that materials at the ocean-silicate interface could  
284 experience even more fracture than we observe in lab. Additionally, while our deformation experiments  
285 are conducted at relatively slow strain rates, they are not identical to timescales and frequencies of tidal  
286 deformation. Under realistic tidal forcing periods, the strength of porous rocks is lower (Bagde and  
287 Petroš, 2009; Peng et al., 2020), increasing the likelihood of cracking in response to small stress changes.  
288 One excellent opportunity for future laboratory studies is the measurement of acoustic properties of  
289 aqueously altered chondritic material, which should exist at the rock-ocean boundary.

290 In addition to releasing heat at the time of their formation, cracks create new surface area. Modeling  
291 by Rovira-Navarro et al. (2022) found that rock-water interaction (via increasing permeability) increases  
292 dissipation throughout a porous core. Fresh surface area would encourage serpentinization, which has  
293 been suggested as a mechanism for generating hydrogen within the oceans of icy bodies (Kamata et al.,

294 2019; McCollom et al., 2022; Neveu et al., 2015; Vance and Melwani Daswani, 2020) or cultivation of  
295 organic materials which have risen to Titan's surface (Castillo-Rogez and Lunine, 2010). Many of these  
296 reactions include volume increase which modifies the local stress field, encouraging further cracking  
297 within the silicate body and providing a self-sustaining heating process.

298

## 299 5. Conclusions

300 We characterized the mechanical properties of stony chondritic material under a range of confining  
301 pressures, defined a failure envelope, measured wavespeeds, and retrieved both static and dynamic elastic  
302 moduli. The mechanical results suggest that porosity decreases significantly at lab confining pressure of  
303 ~50 MPa, such that the silicate interiors of larger icy moons will be relatively dense and impermeable.  
304 The interiors of larger moons are less deformable, and therefore contribute proportionally less energy in  
305 response to tidal forcing, than those of smaller moons. We also observed semi-continuous energy release  
306 arising from microcracking under small changes to stress. These microcracks may represent an apparent  
307 viscous response which enhances heat dissipation within rocky cores and mantles. The energy release  
308 from microcracking occurred during pressurization and depressurization as well, and transmissivity of the  
309 material (likely dependent on its porosity) was a function of current confining pressure rather than  
310 pressure history. Pressure, and the resultant amount of porosity that a material can maintain, is therefore a  
311 strong control on the dissipative potential of silicate interiors. These findings are useful for determining  
312 the level of heat generated in the cores and mantles of icy moons, which may then drive ocean circulation  
313 and/or maintenance. We also see that the release of energy persists as deformation continues, indicating  
314 that ongoing deformation on a diurnal timescale may remain important for the total heat flux of an icy  
315 body.

316

317

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322 interiors, and to Rick Binzel for early input on the project.

323

324 **Data Availability Statement:** All mechanical, ultrasonic, and acoustic data can be found at  
325 <https://zenodo.org/records/10211457> (Seltzer, 2023).

326

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