

Fabric and strain analyses support a unified framework for sediment deposition, relaxation, and glass formation

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ABSTRACT

The kinetic energy of particles at deposition E_k is a distinguishing feature of all near-surface environments, varying due to particle mass and local stress field within the fluid that transports the particles. Once deposited, a granular fabric emerges that exerts control on the subsequent relaxation processes, including on whether, when, and how granular sediments catastrophically fail. Despite advances in characterizing relaxation and the recognition that fabrics emerge from the balance of energy input and energy dissipated during deformation, there is no framework linking this energy balance to the 3D fabrics of sediments after deposition or relaxation events. Here we prepare granular samples with increasing E_k , then quantify the fabrics and relaxation dynamics via X-ray micro-computed tomography and light scattering. Higher E_k leads to less dense, less physically connected, and more structurally heterogeneous packings. These effects resemble those associated with faster quenching in glasses and imply that the energy balance governs the rate at which configurational space is explored. We use phenomenological and theoretical arguments to introduce an energy-based dimensionless deposition number Π_E that characterizes the energy balance and demonstrate its connection with common dimensionless parameters used to study friction, vibration, and flow patterns during relaxation, unifying granular and glass processes.

Introduction

The rigidity of near-surface sediments governs their response to natural forcings^{1–3}, regulates transport pathways for nutrients and fluids that affect habitability^{3,4}, and affects the safety of vehicles⁵, drilling for in-situ exploration or resource utilization⁶, dust and other particle emission^{3,7}, and the anchoring of built infrastructure⁸. Rigidity is a mesoscale property that emerges from the balance of forces and torques transmitted through grain contact networks in sediments^{9,10}. Spatiotemporal changes in the fabric of the material, both the positions of grains and the vector forces at the frictional contacts, can reorganize the network of forces within the material, leading to sub-clusters of more and less rigid zones within the same material¹¹. These fabrics and mesoscale structures evolve¹² under both natural and anthropogenic forcings such as elevated pore-fluid pressures¹³, earthquakes¹⁴, bolide impacts¹⁵, and mechanical drilling¹⁶, making rigidity a history-dependent moving target. This history-dependence most notably complicates efforts to predict if, when, and how natural hazards involving sediment failure [e.g., landslides¹⁷, liquefaction¹⁸, and ground fissuring¹⁹] will occur.

All near-surface sediments susceptible to failure share the common mechanical history of transport, deposition, and subsequent relaxation that influence their rigidity. During mass transport, particles gain kinetic energy that is dissipated primarily through inelastic collisions, sliding, and rolling^{20–23}. Deposition occurs once the external forcing that led to mass transport ceases and sufficient kinetic energy has been dissipated^{20–23}. Subsequent relaxation processes, such as creep, compaction, and diagenesis, are driven by residual internal energy as well as new ambient or anthropogenically-introduced forcing^{23–25}. The grain contact breakage, reformation, and force network reorganization that characterize relaxation modify the quasi-statically arrested fabric²⁶, and hence the rigidity and measured elastic moduli^{9,25,27} of the deposited materials. Understanding the origins of rigidity loss in nature therefore requires advances in determining how transport, deposition, and relaxation shape the [1] force-contact networks and [2] fabric of sediments¹⁴. Whereas in-situ force networks remain inaccessible within the natural sediments, recent advances in in-situ coring and X-ray imaging now make three-dimensional sediment fabrics directly observable¹⁴. This emerging capability motivates our focus on how changes in the energy available during deposition and the initial stages of relaxation shape the fabric of near-surface sediments, which ultimately have

implications for its rigidity.

Lab experiments have demonstrated that the fabrics that emerge from deposition and relaxation are controlled by how acoustic or mechanical energy is introduced and then dissipated through deformation within confined regions of the granular assemblage^{14,28,29}. In the context of deposition, this energy input-dissipation interplay is typically modeled experimentally through particle delivery kinematics and agitation during air pluviation and tapping protocols, where parameters such as fall height, feed rate, or tapping intensity tune bulk density^{30–36}. In shear-driven systems that undergo creep relaxation, researchers commonly parameterize the energy input-dissipation interplay by the inertial number I , which compares the timescales of imposed shear-deformation to the timescale of grain rearrangement under confining pressure^{37–40}. I depends on frictional state and granular temperature T_g ^{29,37–40}, with simulation results suggesting that T_g influences the grain contact fabric and force networks that contribute to bulk friction²⁹. In vibration-driven compaction, researchers express this interplay through the dimensionless acceleration Γ , which quantifies the inertia due to the intensity of external vibrational forcing relative to gravitational confinement^{28,41}. Γ controls the extent to which the configurational space is explored prior to arrest⁴¹, with higher values generally leading to lower volume fraction for $0 < \Gamma < \approx 1$ ²⁸. These advances in understanding relaxation expose two notable gaps: (1) no known corresponding dimensionless parameter captures depositional processes within this energy–dissipation framework, despite deposition setting the initial mechanical state and encoding structural memory that influences subsequent relaxation in natural systems, and (2) no known direct experimental mapping explicitly connects energy input, dissipation, and the resulting three-dimensional fabric across systems.

This study uses laboratory experiments to test whether depositional kinetic energy E_k controls the three-dimensional fabric and initial relaxation of granular materials. We model deposition via air pluviation and systematically vary E_k by controlling the mass flow rate at which we mechanically feed particles into our sample container (Fig. 1). We use X-ray micro-computed tomography (XRCT) and diffusing wave spectroscopy (DWS) to show that increasing E_k increases configurational disorder, reduces elastic moduli, increases the proportion of rattlers, reduces clusters of grains with relatively higher coordination numbers, and increases the global average strain during the first two minutes of relaxation. We also propose a dimensionless number that characterizes the deposition process, demonstrate phenomenological and theoretical connections between granular deposition and relaxation, and argue that increasing E_k produces effects analogous to increasing the glass quench rate — i.e., the rate at which glasses fall out of equilibrium as it approaches structural arrest at the fictive temperature^{42–44}. Studying deposition in isolation therefore provides a direct route to link energy input with emergent structure in confined granular materials, supports a unified description of granular deposition and glass formation, and sheds new light on the origin of mesostructural fabrics that shape the rigidity, and hence susceptibility of failure, in near-surface sediments.

Results

Relationship between E_k and granular fabric

In Fig. 2, we examine how the kinetic energy at deposition E_k affects key bulk and mesostructural quantities: spectral entropy S_{SP} calculated from Eq. 10 and local volume fraction ϕ , rattler fraction f_R , contact anisotropy a , coordination number Z , and contact index CI calculated using SPAM algorithms. We find that all but one of the bulk and mesostructural quantities exhibit decreasing or increasing trends with E_k .

As shown in Fig. 2A, we observe that S_{SP} increases with E_k for S2–S6, ranging from 6.98 (S2) to 7.17 (S6), with all values having a standard error across all XRCT slices of about ± 0.003 . S1 has an anomalously high S_{SP} value but is still comparable to the value for S3. For ϕ (Fig. 2B), we observe the opposite trend: the samples become looser-packed as a function of E_k , ranging from 0.639 ± 0.002 (S2) to 0.611 ± 0.002 (S6). As in S_{SP} , S1 has a ϕ similar to S3, which likewise causes a departure from an otherwise decreasing $\phi - E_k$ trend. Supplement Figs S1–S2 show that the ϕ distributions are leptokurtic and that no clear trends exist with E_k in the second through fourth moment. Together, these quantities illustrate that higher E_k promotes structurally more complex, but less dense granular packings.

We test how increasing E_k changes the load-bearing contact network via examining changes to the samples' rattler populations and contact fabric anisotropy. As shown in Fig. 2C, the fraction of rattlers f_R has a trend similar to S_{SP} ; notably, S2 breaks from similarity. We observe a rattler fraction of $f_R \sim 0.06$ for all four lowest-energy feed rates, before increasing to almost twice that value for S5 and S6. Meanwhile, the bulk scalar anisotropy a exhibits no clear dependence on E_k , as shown in Fig. 2D. Interestingly, we observe that $a_r \sim 0.5$ is greater than $a_{nr} \sim 0.2$ for all feed rates, with some evidence of a slight increase in a_r as a function of E_k . Taken together, the f_R and a_r results suggest that the number of grain-grain contacts are a driving factor in our results.

Further examining the number of grain-grain contacts, Fig. 2E–F shows that $\bar{Z}$ and its standard deviation have decreasing trends as a function of E_k . These $\bar{Z}$ values are significantly affected by contact networks which are more dominated by large- Z outliers ($Z = 8$ to 14) at lower values of E_k , even while most grains have $Z \approx 4$ to 7 . This is quantified by all samples exhibiting moderate right skewness (≈ 0.7 ; see Fig. S3); the excess kurtosis is close to 0.4 for all except in S2, which was an outlier in other measures mentioned above. Another useful way to view the contact network, shown in Fig. 2H, is via the grain contact

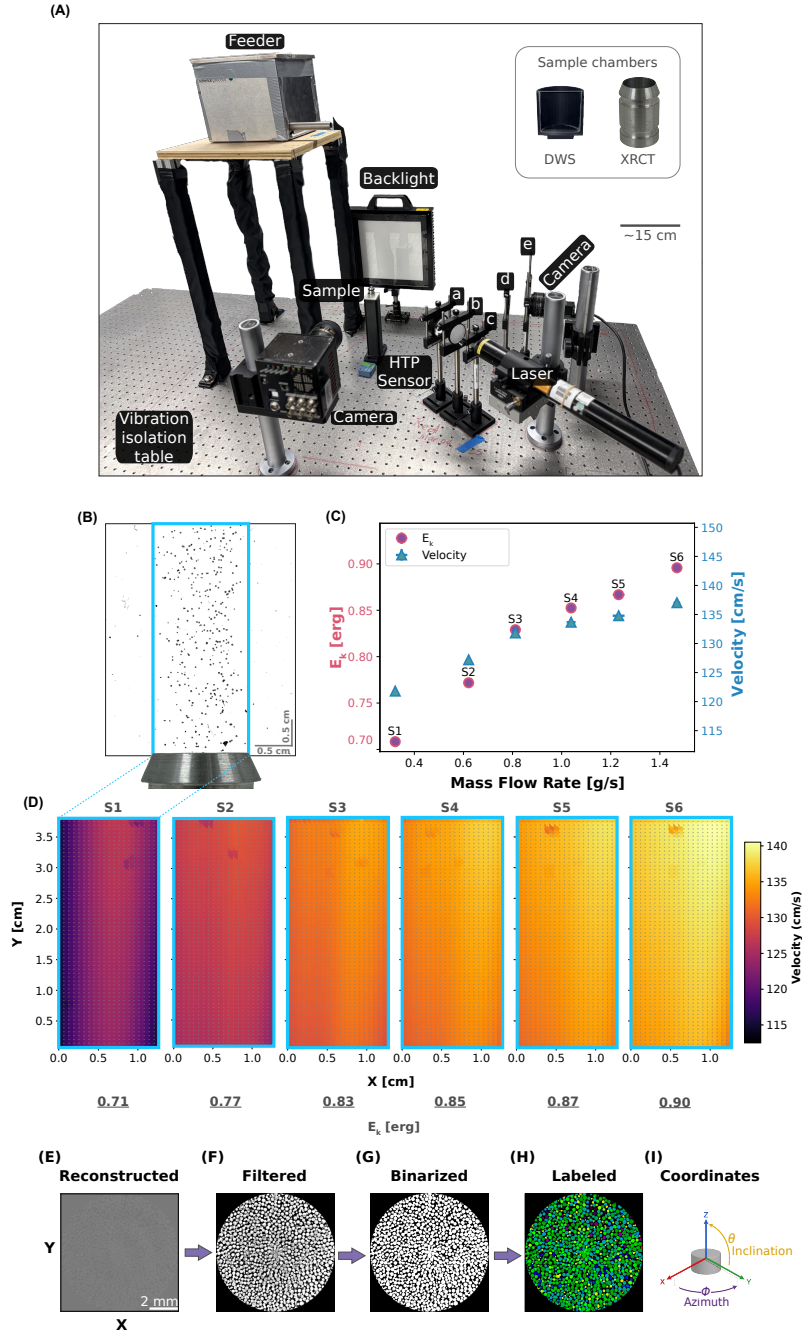


Figure 1. (A) Experimental setup for air pluviation and diffusing wave spectroscopy (DWS). DWS components — a : collimating lens ($f = 75$ mm), b : holographic diffuser (30° half angle), c : beam expander ($10\times$), d : linear polarizer, and e : optical filter (633 ± 5 nm), with further specifications in Table S2. HTP — humidity and temperature sensor. Inset shows sample chambers used. (B) Example image of falling glass beads captured by the camera. Light blue box is the region of interest used to calculate particle velocities. (C) Mean kinetic energy E_k and mean velocity v compared with measured mass flow rate of each sample. Standard errors across all measurements within the blue region are shown as error bars; all are smaller than the marker size, except for sample S5. (D) Color maps of the mean particle velocity used to calculate E_k . (E)-(H) are 2D image slice example outcomes of the main steps in the processing of the XRCT radiographs: (E) reconstructed raw image, (F) filtered image, (G) binarized image, and (H) labeled image. (I) Coordinate system outlining the orientation of azimuth (horizontal radial orientation in the X-Y plane, increasing to Y) and inclinations (vertical orientation from X-Y plane to the Z-axis, increasing to Z) within the sample.

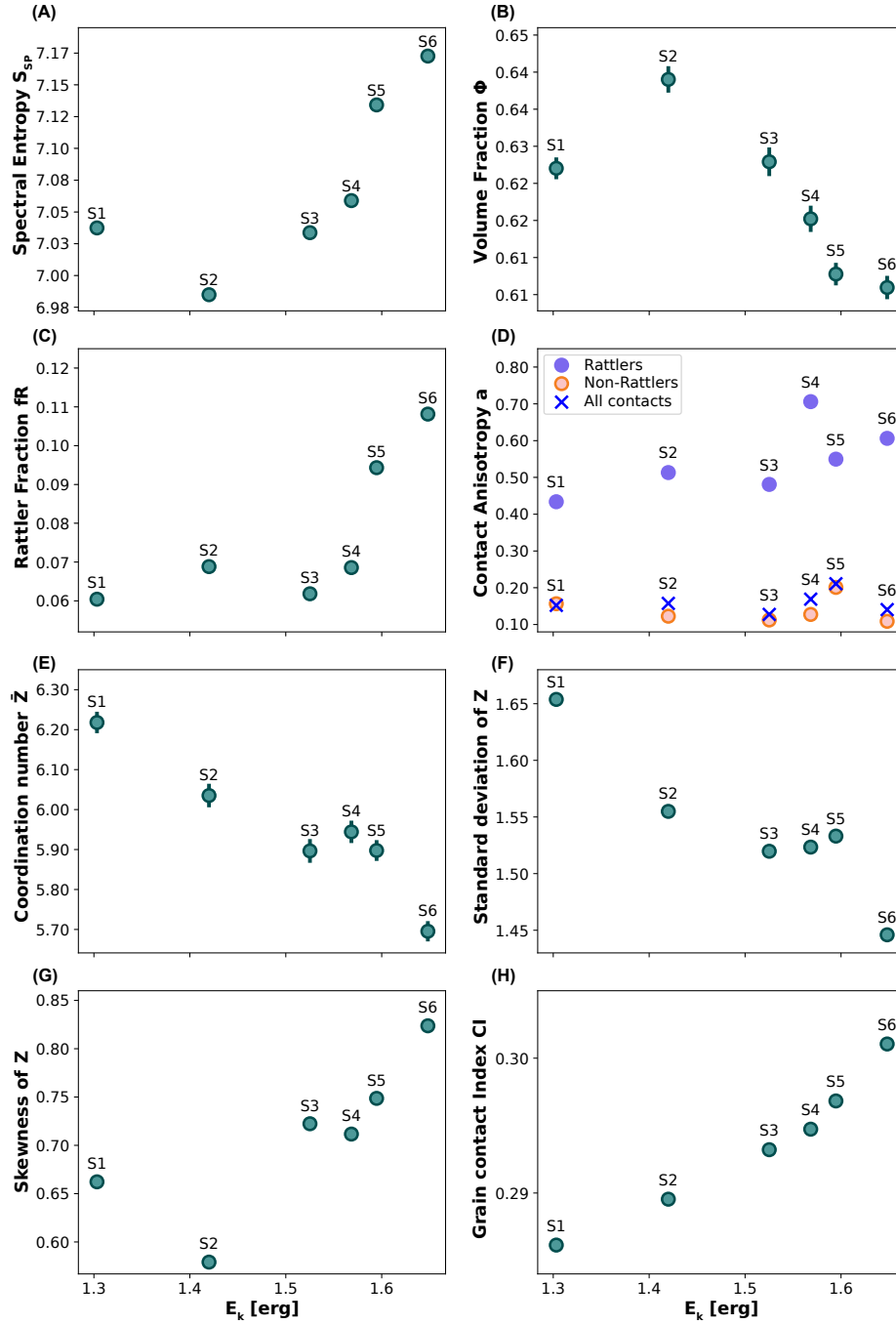


Figure 2. Structural properties as a function of kinetic energy E_k . (A) Mean spectral entropy S_{SP} vs E_k . S_{SP} error bars are smaller than the marker size and represent the standard error across all slices (B) Mean local volume fraction ϕ vs E_k . Error bars of ϕ represent standard error of the local volume fractions. (C) Rattler fraction f_R vs E_k . (D) Mean contact anisotropy a of all grain contacts, rattlers a_r , and non-rattlers a_{nr} vs E_k . Standard error on both a_r and a_{nr} are smaller than the marker size. (E) Mean Coordination number $\bar{Z}$ vs E_k . Error bars on $\bar{Z}$ represent the standard error. (F) Standard deviation of Z vs E_k . (G) Skewness of Z vs E_k . (H) Grain contact index CI vs E_k . Standard errors of all E_k are smaller than the marker size.

index CI . This measure increases monotonically by a small amount as a function of E_k . The trends in Fig. 2 indicate that increasing E_k creates a contact network with fewer and more anisotropic contacts: this likely means that it is less rigid¹⁰ and has lower bulk elastic moduli and higher bulk compliance⁴⁵.

In lieu of estimating rigidity, elastic moduli, and compliance in the present experiment, we investigate how E_k influences

the distribution of local clusters of grains $I_{i,Z}$ with relatively high and/or low coordination numbers (Fig. 3) reported in Fig. 2E, while simultaneously being largely insensitive to pore volume V_{po} (see Fig. S4–Fig. S6). Here, we define a number of local neighbors n within the samples' contact network through their coordination number Z , and find that clusters grains with high Z exhibit a decreasing trend with E_k , whereas clusters of low Z grains and low Z grains surrounded by high Z grains exhibits a general increasing trend. These trends are generally insensitive to n . The low-high Z cluster fractions slightly increases, though there is significant scatter. High-low Z cluster fractions remain roughly uniform with E_k (Fig. 3B). Notably, $I_{i,Z}$ versus E_k clusters segregate into two, non-overlapping groups based on n — $n \leq 6$ grouping and $n \geq 10$ grouping — for high-high and high-low Z cluster fractions. No such segregation is present for low-high and low-low Z cluster fractions, and no trends exist between the global spatial autocorrelation I_g with increasing E_k (Fig. 3E).

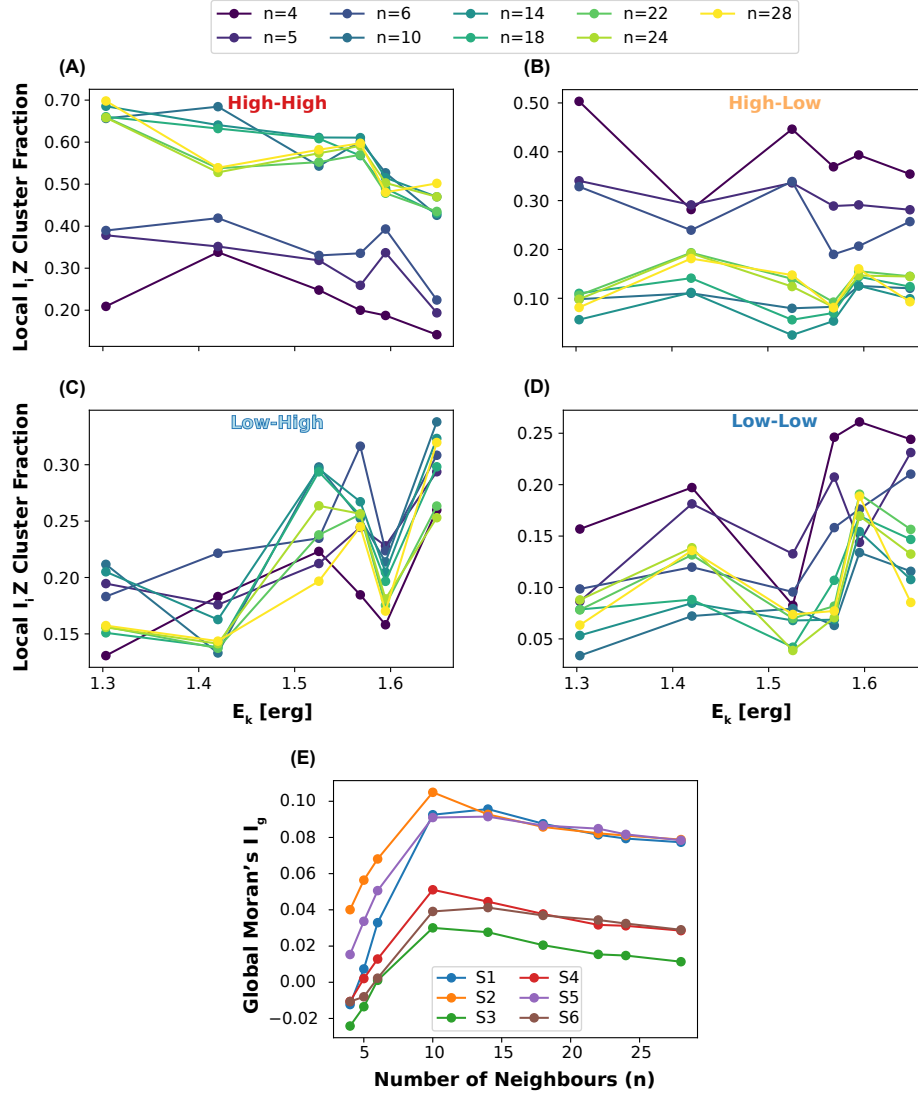


Figure 3. Fraction of the four types of I_i clusters — (A) High-High, (B) High-Low, (C) Low-High, (D) Low-Low — based on mean integer coordination number Z^* for all samples. I_{i,Z^*} was calculated for 9 different number of neighbours n and the fractions show a dependence on E_k . (E) Global Moran's I value I_g of each sample. I_g shows no dependence on E_k . Standard error of E_k is smaller than the marker size. Note, y-axes on (A) - (D) are not the same scale.

In Fig. 4 and Fig. S7, we use stereonets to examine the orientational distribution and preferences of our branch vectors, comparing our observed distributions with 500 simulations that assume random orientation on a sphere and reporting deviations from randomness using Z-scores. We find that rattlers exhibit inclinational preference but neither rattlers nor non-rattlers exhibit azimuthal preferences. Rattlers contacts preferentially orient from sub-horizontal ($\theta \sim 30^\circ$) to vertical ($\theta \sim 90^\circ$) across all azimuths (Fig. 4A). Compared to non-rattlers (Fig. 4B), rattlers display stronger orientational clustering, with all rattler contact

stereonets having regions where Z-scores exceed 0.5. At the highest three E_k (S3-S6), peak densities exceed Z-scores of 0.7 and are concentrated at sub-vertical ($\sim 60^\circ$) to vertical inclinations. In contrast, non-rattlers contacts (Fig. 4B), as well as all contacts combined (Fig. S7), show little preference in either inclination or azimuth. The diffuse distribution of Z-score values mostly below 0.2 indicate that only minor deviations from a random orientation exist within these samples.

All trends reported above have had their error bars determined by changing the local thresholds that we use for grain-contact detection (Fig. S8). Doing so leads to $\bar{Z}$ reducing by a maximum of one, but the $\bar{Z}$, CI , a_r , a_{nr} , and fR trends remain largely the unchanged. We provide details in Fig. S8. Furthermore, we see no trends between E_k and either of pore volume or shape; pore volume distributions are notably best described by a stretched exponential form (see Text S4 and Figs. S4–S5, S9–S13).

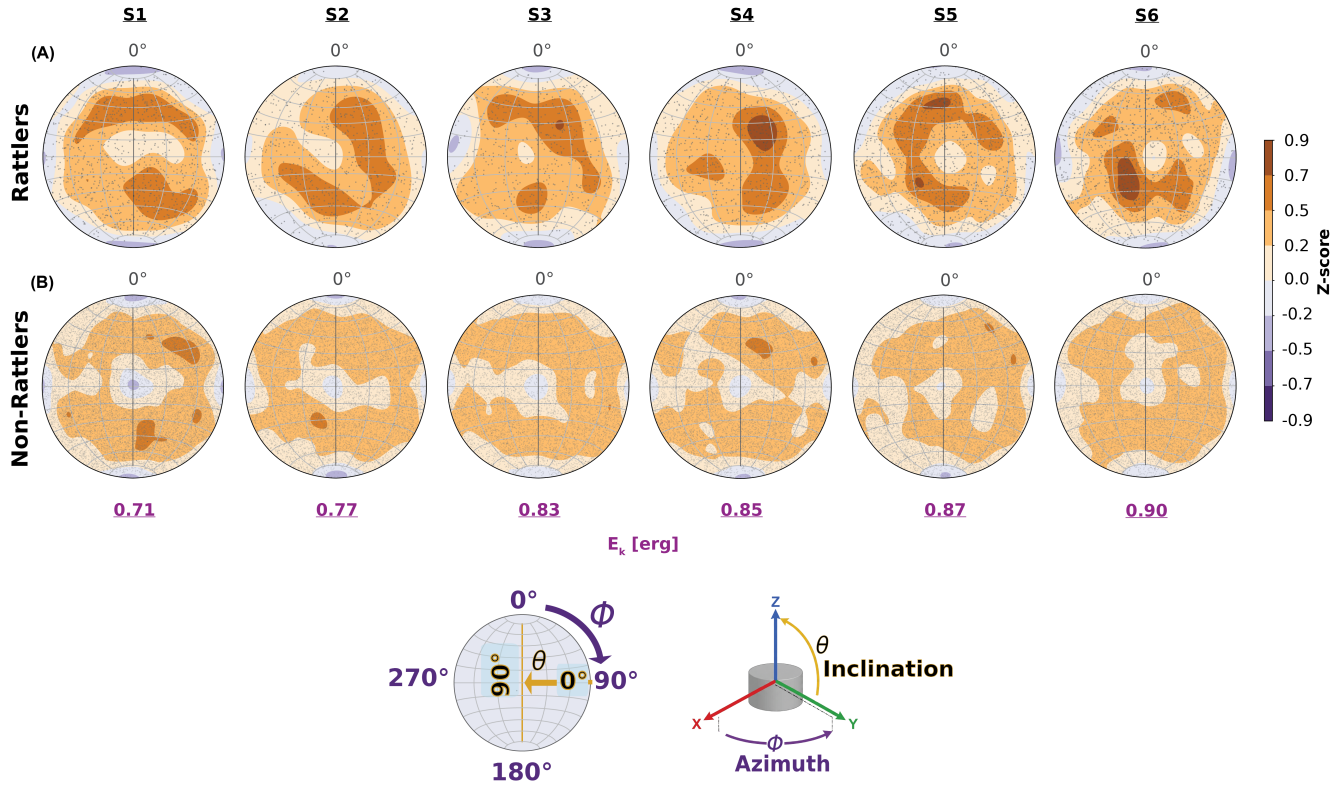


Figure 4. Density-contoured stereonets of the orientations of the contact vectors for (A) rattlers and (B) non-rattlers. At the bottom center are schematics showing the azimuths labels for the stereonets and the coordinate system for the sample. Light gray dots on the stereonets are the observed v_i orientations. Contours and colors represent the Z-score derived from comparing our values to the outcome of 500 simulations of random, uniform contact vector distributions, following the method of Kamb (1959)⁴⁶. A positive (negative) z-score indicates that our data has a higher (lower) density of points than the random distributions.

Relationship between E_k and relaxation dynamics

The fabric described above is a result of E_k and the relaxation that occurs during and after pluviation ends. Here, we analyze the global average strain from DWS measurements to determine the rate at which each packing relaxes to a steady state. As shown in Fig. 5 and Fig. S14, we observe that the strain at $t = 0$ (the start of the observation period) is largest, and decays to a background level ($\sim 0.8 \times 10^{-6}$) within about 5 minutes. This means that our XRCT measurements were all stationary enough to collect data on static packings. Note that the mean strain within the illuminated area of the sample varies among the five independent runs for each E_k , and we do not observe any reason to expect systematic sources of error due to the time or order in which we took the data.

However, the initial state is highly dependent on E_k : the largest initial strains are observed for systems with larger kinetic energy, as expected, and the lowest final strains for lower kinetic energy. The standard error taken across all 5 runs also decreases with the feed rate. In spite of this, the aging process (decline in ϵ with time) is quite similar in all cases. We did observe one sample (S6) which fell out of order (lower values than for S5). Overall, these observations indicate that the magnitude of particle collision and rearrangements after mass transport ceases scales with their kinetic energy during transport.

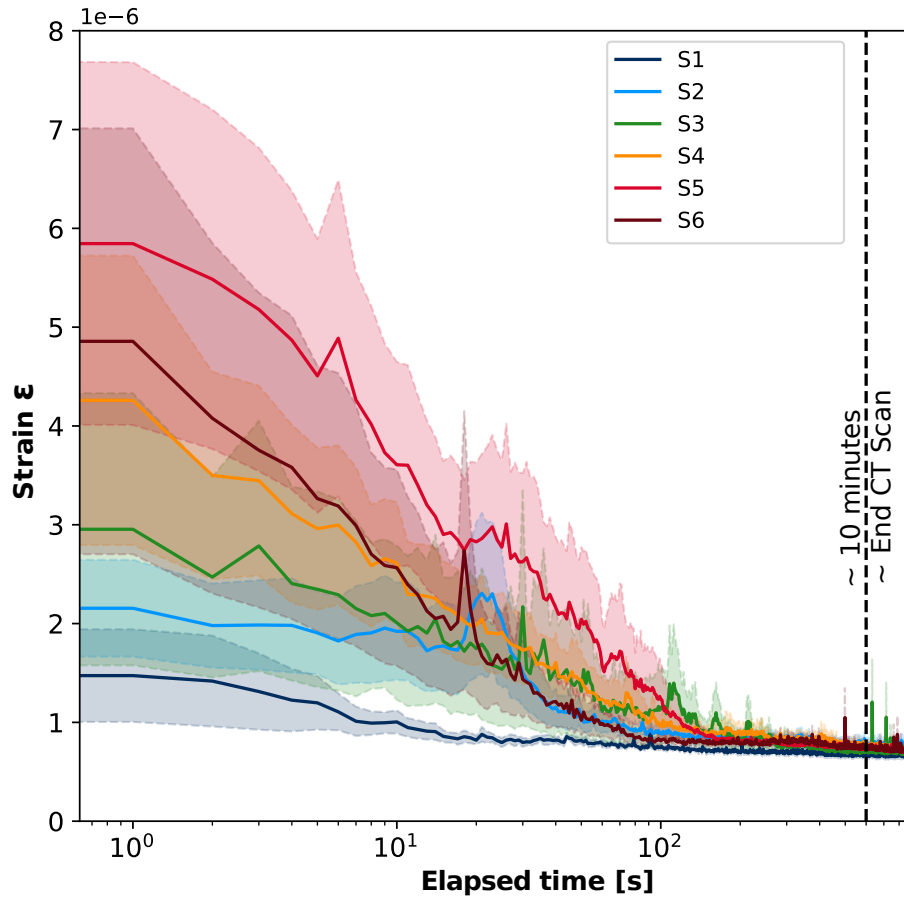


Figure 5. Mean strain ϵ of each sample during 1 s intervals, reported for ~ 10 minutes after the container is full and grains are no longer being added to the pile. Data is captured using the diffusing wave spectroscopy set-up. The shaded regions represent standard error over 5 runs.

Discussion

We have shown that E_k influences both the mesostructures (S_{SP} , a , I_i) and bulk properties (ϕ , $\bar{Z}$, CI , ϵ) of granular materials, with small deviations likely arising from run-to-run variation and humidity/temperature effects. Here, we discuss how our results can be used to understand the relationship between energy input, dissipation, and the resulting granular fabric during deposition and relaxation.

Kinetic energy at deposition and the glass quench rate

Drawing inspiration from the study of glasses, we interpret our results to assess how the preparation protocol shapes the internal fabric, and in turn, affects the macroscopic properties of the granular packings. The quenching of glasses occurs via a process similar to pluviated deposition: in both cases, the material undergoes a dynamic transition from a fluid-like to solid-like state over some finite timescale and within a confined volume. It is well known that faster quenching of glasses governs the mesostructural parameters that control the elastic moduli and mechanical properties of the glass such as its brittleness or ductility^{47–52}, and that quenched glasses undergo aging, during which particles slowly rearrange to create new mesostructures with new corresponding bulk properties^{42,53}. These mesostructures emerge because faster quenching limits the time available for structural relaxation prior to arrest, which causes higher-energy configurations to become frozen into the material^{42,44,54–56}. Establishing whether or not E_k acts analogously to the glass quench rate could therefore provide future opportunities to connect granular deposition and fabric evolution to broader theoretical frameworks developed for glasses and other dynamically arrested materials.

Increasing configurational disorder is a hallmark of glassy materials quenched at increasingly high rates^{51,57,58}, and our results suggest that increasing E_k produces a similar effect in granular materials. The most direct evidence is the general trend of increasing S_{SP} with increasing E_k , and this is also consistent with the observed relationships between E_k and ϕ , CI , Z and its moments, f_R , and the distribution of $I_{i,Z}$ clusters. Configurational disorder has been previously observed to evolve systematically with ϕ ⁵⁹ and $\bar{Z}$ ⁶⁰ in granular materials, while f_R increases with decreasing $\bar{Z}$ and ϕ ⁶¹. Accordingly, the decreases in $\bar{Z}$ and ϕ , together with the increases in CI and f_R , indicate increasing structural heterogeneity consistent with higher S_{SP} . The higher prevalence of lower- Z regions, reflected in the decrease in the fraction of high-high $I_{i,Z}$ clusters and the increase in the number of low-low clusters, bolsters the interpretation that increasing E_k increases structural heterogeneity.

In glasses, faster quenching also leads to greater elastic moduli and free volume, both of which we infer to increase with increasing E_k based on the trends in ϕ , S_{SP} , and ϵ ^{47,48,50–52}. From the Hertz-Mindlin rock physics theory, elastic moduli increase with increasing ϕ and Z , which has also been validated experimentally⁴⁵. Free volume, on the other hand, is challenging to directly measure experimentally^{51,62}, but is the counterpart of ϕ and has been shown to scale with configurational entropy^{47,48,52}. Beyond the ϕ (the mean of our ϕ_L) we see no relationships with E_k and higher order moments of ϕ_L (Figs. S1, S2) but the samples' ϕ_L distributions all being negatively skewed and leptokurtic (excess kurtosis > 8) (Fig. S2C-D) suggest that while the free volume in our samples are not energy-dependent, it is mostly randomly distributed in areas of similar sizes, with localized areas of higher free volume. We further infer that the elastic moduli of the samples decrease with E_k , as elastic moduli and bulk density decrease with increasing free volume^{47–49,51,52}. During aging, glasses densify, reducing free volume and relaxing toward lower-energy states^{48,51,63}. The increase in post-depositional relaxation with increasing E_k , evidenced by the increasing strain as a function of increasing E_k over the first ~ 10 minutes after deposition, is consistent with a more slowly relaxing, less mechanically stable state. These inferred decreasing free volume provides additional evidence that depositional E_k may play a role analogous to the quench rate in glassy materials.

Underlying mechanisms

In direct analogy to the quench rate in glasses^{42,44,54–56}, we propose that the relationships between E_k and post-depositional structural parameters reflect the finite timescale over which particles form and maintain contacts prior to arrest. As particles are deposited, incoming grains interact with the surface of the growing pile and act as localized sources of mechanical perturbation that enhance grain agitation within a localized volume (Fig. 1B). This increased agitation promotes more frequent grain contact breakage, avoidance, and reorganization that causes particles to explore larger region of the configurational space prior to jamming. As highlighted for glasses, greater exploration of the configurational space reduces the likelihood of stabilizing locally dense regions in the material^{42,44,54–56}. Therefore, we expect the same process to be the likely cause of the observed decreases in $\bar{Z}$, ϕ , and the fraction of clusters of high coordination number with increasing E_k in granular materials. The reduction (increase) in clusters of high (low) coordination numbers, together with the lack of increase in global spatial autocorrelation, suggests that clustering remains localized.

The aging process described above is also consistent with observations from other post-depositionally driven granular systems, where external forcing, whether through shear, vibration, or tapping controls flow via the balance between dynamical agitation and energy dissipation^{28,29,38–41,64,65}. The mechanical perturbation from the incoming particles produce vibration that propagate throughout the material. Discrete element modeling simulations show that externally introduced vibrations can

influence macroscopic friction during shear-induced flow of dense granular materials via the functional relationship between I and T_g , and that this may occur partly due to changes in the contact fabric²⁹. Notably, low I or T_g regimes are characterized by long-lived contacts and localized rearrangements, whereas higher values promote frequent contact breaking, and reduced force-chain persistence²⁹, as we suggest for deposition. Elsewhere, in systems that are vibrated or tapped post-deposition, the ratio of energy input per cycle to confining stress, Γ , governs the rate of compaction primarily because it impacts the accessibility of metastable states, with relaxation occurring during intervals of low agitation^{28,41}. Accordingly, the fundamental difference between our and existing systems is that the total energy available for rearrangement is supplied during deposition and dissipated continuously as the system approaches arrest. Thus, the relevant control parameter is not the instantaneous forcing, but the integrated energy available prior to arrest. All other systems are subjected to history of preparation effects, whereas studying deposition in isolation allows us to more directly examine the relationship between energy injection, fabric, and relaxation.

Motivated by the observation that shear, vibration, tapping, and deposition all inject energy that is subsequently dissipated through particle rearrangements, we seek a parameterization based directly on the balance between energy injection and confinement, then examine its relationship to existing dimensionless parameters used in granular flow. We begin by defining a deposition number Π_E as the ratio between the incoming kinetic energy of the particles E_k (inertial effects) and the characteristic energy needed to re-arrange the particles within the packing (confinement effects):

$$\Pi_E = \frac{E_k}{Pd^3} = \frac{\rho v^2}{P}, \quad (1)$$

where P is the confining pressure and d is a characteristic grain diameter. Although P and grain-scale properties are approximately constant across our experiments at different E_k , this scaling predicts that natural systems would experience systematic dependence on depth through P and on grain size and density through d . Interparticle friction, force-chain heterogeneity, and fabric anisotropy will also influence the energy required for rearrangement⁶⁶. We absorb these effects into the scaling presented here, though corrections to the simple Pd^3 scaling may be needed to account for those effects.

Relationship between deposition and relaxation

We now quantitatively show that the similarities in the phenomenologies between granular deposition and relaxation occur because they share a common mechanistic origin: Π_E can be related to the inertial number $I = \frac{\dot{\gamma}d}{\sqrt{P/\rho}}$ ^{37–39} (with shear rate $\dot{\gamma}$) and T_g that has been used to describe granular relaxation processes such as creep and dense homogeneous flow. Our derivations aim to demonstrate scaling relationships between these quantities, not equivalence as the different systems require differing assumptions regarding the dominant rearrangement mechanisms. First, we assume that particle rearrangements due to mechanical perturbation on the top of the pile during deposition are local, not ballistic, and occur through shearing (sliding and rolling) over a distance of order d and with a characteristic particle velocity $v \sim \dot{\gamma}d$. Under these assumptions, Eq. 9 is simply

$$\Pi_E \sim \left(\frac{\dot{\gamma}d}{\sqrt{P/\rho}} \right)^2 = I^2, \quad (2)$$

also known as the Savage number⁶⁷. This illustrates that Π_E can be interpreted as describing the deposition of granular materials in terms of a ratio of two timescales, or the ratio of two energy scales. Deposition is not a steady shearing process, which makes this correspondence a scaling argument rather than a proposal of strict equivalence.

The definition of a granular temperature $T_g \sim \langle v^2 \rangle$ provides another energy scale, since E_k is the dominant source of particle velocity fluctuations in our system. This yields

$$\Pi_E \sim \frac{\rho T_g}{P}, \quad (3)$$

where Π_E now represents the ratio of fluctuation energy to confining stress. This provides a rationalization for comparing the results of the effects of T_g on friction and the mesostructures in dense granular flow. In nature, this scaling will depend on the extent to which deposition controls the particles' velocity fluctuations prior to arrest. In systems where dissipation is rapid or fluctuations remain highly localized, deviations from this relationship may occur.

Implications

By establishing experimental, phenomenological, and theoretical links between deposition, relaxation, and glass formation, this work provides a framework for beginning to address several longstanding questions related to the failure of natural sediments. Why does one region of Earth's near surface preferentially deform or fail while an adjacent region, subjected to nearly identical

external forcing, remain stable? What controls the frictional resistance, and hence rigidity and yield point, of sediments that do fail? Through what mechanism does vibration-induced frictional weakening emerge in sediments, including those that define fault gouges?

Our results suggest that one contributing factor to the spatial variability of sediment failure events may be inherited depositional fabric, which varies with the kinetic energy available during transport and deposition. If subsequent forcing does not erase or substantially modify the initial depositional fabrics (both its connectivity and the orientation of that connectivity), then differences established at deposition will either persist over geologic timescales or shape how fabrics evolve during subsequent relaxation¹⁸. These fabrics likely contribute to the spatial variability in creep, strain localization, and mass failure since each region of Earth's near surface possesses its own material-dependent yield point. Work with photoelastic materials for which vector contact forces are measurable⁶⁸ reveals that the fabric of the contact network alone (even without considering interparticle forces), is able to predict much of the internal friction angle of the bulk material. Future work using 3D X-ray diffraction would be able to test for the same effect in 3D granular materials⁶⁹. A key next step is also to determine how energy injection and dissipation during relaxation modify, preserve, or erase the depositional memory encoded within the granular fabric.

The demonstrated relationships between Π_E , I , and T_g , together with the findings that E_k shapes granular fabric, can help direct future research on how vibration-induced frictional weakening leads to failure. Existing studies propose that vibration-induced frictional weakening arises through coupled changes in bulk contact fabric anisotropy and the distributions of normal and tangential contact forces within the material^{23,29,70}. Notably, contact fabric anisotropy changes do not vary systematically with increasing E_k in our spherical packings, whereas coordination number, configurational disorder, and initial post-depositional relaxation respond much more strongly. These observations suggest that changes in rigidity and friction may arise initially through modifications to the load-bearing contact network and its mesoscale organization before appreciable changes in the contact anisotropy develops. Measurements of three-dimensional force networks^{69,71} will be important for testing this hypothesis. Finally, recent advances that relate yielding to distance from jamming⁷², alongside the ability to preserve and examine in-situ fabrics in 3D¹⁴, may allow us to conduct experiments on natural material to determine if and how Π_E contributes to their evolving rigidity state, which would allow for improving area-specific forecasts of sediment failure.

Conclusion

We examine the post-depositional fabrics of laboratory samples that we prepare by air-pluviating glass beads at six different kinetic energies, E_k . Our analyses reveal that increasing E_k systematically shapes the mesostructural fabric and macroscopic properties of the deposited materials. Packings prepared with higher E_k are more configurationally disordered, form fewer grain-grain contacts per particle, and develop a higher fraction of rattlers. Their coordination numbers and mean local volume fractions are lower; they develop fewer clusters of grains with high coordination number, and they generally experience higher mean strains in the packing during the first few minutes after deposition. These properties and relaxation dynamics are reminiscent of glasses quenched at higher rates, and highlight that the fabric at deposition may be understood as a consequence of how broadly the configurational space is explored prior to structural arrest.

We use our observations and understanding of glass formation to propose a dimensionless depositional number Π_E that characterizes the balance between injected and dissipated energies in the granular packing. Under the assumption that rearrangement is mediated by shear or vibration, we analytically show that Π_E scales with granular temperature T_g and inertial number I , both of which are known to influence friction and hence the rigidity of dense granular flows. Accordingly, our results and analytical findings establish a unified framework linking glass formation, depositional energy, granular fabric, and the anticipated rigidity of granular media. Future work could involve a more in-depth analysis of how injected energy shapes the relaxation dynamics of idealized and natural granular systems, alongside developing techniques for directly measuring rigidity in three-dimensional granular systems.

Methods

Sample preparation and energy analyses

We use a Schenck Process Accurate Series mechanical feeder to prepare six samples with increasing kinetic energy E_k . For the experiments, we first dry the particles for one hour at 60°C, then place them inside the feeder's enclosed chamber, where a desiccant silica gel packet further reduces moisture. The feeder fills our 12.7 mm-inner-diameter, 25.4 mm-high cylindrical sample container from a height of 40 cm above the container top. The feeder releases grains from its storage chamber using a motor-driven spiral spindle, which rotates at a user-defined number of revolutions per minute. We extrude grains at six rates, scaled by the maximum spindle rotation: 13.6%, 23.7%, 33.9%, 44%, 54.1%, and 64.2%. We designate the corresponding feed rates S1 through S6 (Fig. 1).

We calculate both the mass flow rate of the pluviated grains and the primary contributions to the grains' kinetic energy prior to deposition, $E_k = \frac{1}{2}mv^2$, using their mass m and falling velocity magnitude v . Here, $m = \frac{4}{3}\pi r^3 \rho_g$, where $r = 250 \mu\text{m}$ is the mean grain radius and $\rho_g = 2.65 \text{ g/cm}^3$ is the mineral density for quartz⁷³. To measure v from particle displacements, we backlight the falling grains and record high-speed images at 6400 Hz with a Fastcam Mini AX 200 camera (pixel size = 20 μm ; resolution = 1024×1024). We use PIVLab^{74,75} to extract the velocity field from these images (see Table S1 for PIVLab analysis details). The mass flow rate provides a bulk measure of the particle flow that we compare to the grain scale kinetic energy. To calculate the mean mass flow rate of the grains, we fill, weigh, and time the filling of the sample container at each feed rate ten times. Mass flow rate is then the ratio of the weight of the filled container to time required to fill.

XRCT image acquisition and processing

We obtain XRCT scans at the Advanced Light Source Synchrotron (beamline 8.3.2) for six samples (S1 to S6, one for each of the six different feed rates) that we prepared on-site. We begin scans within ~ 60 seconds of filling the sample container, which reflects the time to safely load the sample unto the beamline and our desire to acquire images of the frozen-in granular depositional fabric. We perform the scans using the Pioneers in Cameras and Optoelectronics edge camera, an Olympus lens, and a 50 mm LuAG scintillator on the beamline. We image with monochromatic light and capture 1969 projections over 180° rotation with 0.2 s exposure times. We reconstruct the resulting 3D stack of 2D images using TomoPy algorithms⁷⁶. The images have voxels with linear dimensions of 3.24 μm .

We filter, binarize, and label the images in Fiji^{14,35,77,78}. We first apply contrast-limited adaptive histogram equalization (CLAHE) to enhance local contrast between grains and pores in the raw images. We then denoise and smooth the images sequentially using a non-local means denoising algorithm⁷⁹, 3D Gaussian-blur filter, 3D median filter, and finally the CLAHE filter again. We binarize the images using global Otsu thresholding on each slice. We assign unique labels to each grain using the distance transform watershed 3D algorithm (distances = Borgefors (3,4,5)⁸⁰, normalise, dynamic = 3, and connectivity = 6). After labeling, we use a MorpholibJ's fill label holes function (background connectivity = 6) to re-establish the contacts between grains that the watershed process removes.

Fabric analyses

We use Software for Practical Analysis of Materials (SPAM)⁸¹ to compute the mean local volume fraction ϕ , coordination number Z , grain center of mass, and contacting grain pairs from the images we obtain from XRCT scanning. We first identify and remove grains not completely imaged by the scan. We calculate the local volume of each grain using a Voronoi tessellation with a maximum pore radius of 20⁸², resulting in a local Voronoi cell volume for each grain. The local volume fraction ϕ_L is the ratio of the grain volume to its local Voronoi cell volume, and we use cells with $\phi_L < 1$ to compute the mean ϕ . For properties requiring knowledge of which grains are in contact, the algorithm assigns a contact pair when two labeled grains share voxels, which we identify contacts following the methods of Wiebicke et al.⁸³. We set the local threshold to the Otsu threshold greyscale value calculated during image binarization, and both greyscale and watershed images are used to detect and refine contact detection, accounting for partial voxel effect. Furthermore, we assess the sensitivity and robustness of our contact refinement by varying the choice of local threshold value by adding 0.01 to 0.08 to our scaled decimal Otsu threshold greyscale value; this provides error bars on our measurements.

From the identified refined contacts, we calculate the mean and the first four moments of Z . We classify grains with $Z < 4$ (the frictional isostatic limit is $Z_{\text{iso}} = 4$ ^{9,84–86}) as rattlers, and calculate the fraction of rattlers f_R as the number of rattlers divided by the total number of grains. We also define a *grain contact index* CI as the ratio between the total number of grains and the total number of contacting grain pairs. CI is a global measure of how dense or sparse the contact network is.

We quantify the degree of spatial correlation in Z within a defined local neighborhood of the reference quantity Z_i using the Anselin Local Moran's I_i ^{87,88},

$$I_i = \frac{Z_i - Z^*}{\sigma^2} \sum_{j=1}^N w_{ij}(Z_j - Z^*), \quad (4)$$

where Z^* is the mean, σ^2 is the population variance, w_{ij} is a row-standardized weighting matrix in which the defined nearest neighbors are equally weighted, and Z_j are the neighboring values of Z_i . We detect clusters using the sign of I_i , the relative magnitude of Z_i with respect to Z^* , and a significance threshold of $p\text{-value} \leq 0.05$. Positive values of I_i indicate clustering of similar values, whereas negative values indicate spatial outliers. For I_{i,Z^*} , we use $Z^* = 5.99$ because 6 is the nearest whole number to the observed mean coordination number in each sample (this means our samples are hyperstatic relative to Z_{iso}). Alongside I_i , we also calculate the global Moran's I_g (ranges from -1 to 1) to quantify sample-scale correlations:

$$I_g = \frac{N}{W} \frac{\sum_{i=1}^N \sum_{j=1}^N w_{ij}(Z_i - Z^*)(Z_j - Z^*)}{\sum_{i=1}^N (Z_i - Z^*)^2}, \quad (5)$$

where $W = \sum_{i=1}^N \sum_{j=1}^N w_{ij}$. We calculate both I_i and I_g using contributions from its $n = 4, 5, 6, 10, 14, 18, 22, 24$, or 28 nearest neighbors, removing any cluster within 3 grain diameters of the sample edge. Within our data, we focus on four local cluster types relative the mean contact number Z^* : high-high ($Z_i > Z^*$ surrounded by $Z_j > Z^*$), low-high (low Z_i surrounded by high Z_j), low-low (low Z_i surrounded by low Z_j), and high-low (high Z_i surrounded by low Z_j).

We use the grains' centers of mass to determine the azimuth and inclination of the contact vector $\mathbf{u}_i$ for the i^{th} contacting grain pair. We then compute the contact vector fabric tensor⁸⁹,

$$\mathbf{F} = \frac{1}{N} \sum_{i=1}^N \mathbf{u}_i \otimes \mathbf{u}_i, \quad (6)$$

where N is the number of contact vectors and $\otimes$ signifies an outer product operation on the contact vectors. The deviatoric component,

$$\mathbf{D} = \frac{15}{2} \left(\mathbf{F} - \frac{1}{3} \mathbf{I} \right) \quad (7)$$

with $\mathbf{I}$ as the identity matrix, allows us to derive the contact fabric scalar anisotropy for the entire sample^{83,90,91}

$$a = \sqrt{\frac{3}{2} \mathbf{D} : \mathbf{D}}, \quad (8)$$

as well as for the rattlers a_r and non-rattlers a_{nr} , where $:$ signifies a double dot product operation on $\mathbf{D}$. To determine our error bars, we simulate voxel-level errors by varying each coordinate point of each contact vector randomly by $-1, 0$, or 1 over 500 trials. We calculated a_r and a_{nr} each time and report the mean and standard errors.

We calculate spectral entropy S_{SP} to quantify structural complexity⁹²⁻⁹⁴. We (1) select the region of interest on the binary images to reflect the circular region of the scan occupied by grains and pore, (2) compute the power spectrum $P(k_i)$ for a set of discrete wavenumbers k_i , (3) normalize $P(k_i)$ by the number of frequency bins N to remove any sampling-rate dependencies, (4) calculate the probability density function p_i for each frequency k_i ,

$$p_i = \frac{P(k_i)}{\sum_{i=1}^N P(k_i)}, \quad (9)$$

and (5) compute the spectral entropy, a scalar measure of the information content of the system:

$$S_{SP} = - \sum_i^N p_i \ln p_i. \quad (10)$$

Relaxation analyses

For five samples prepared at each of the six feed rates (S1 to S6), we obtain DWS measurements to quantify their global relaxation dynamics during the first ten minutes after deposition. We chose this duration to match with the time it takes to obtain a XRCT scan of the samples. Fig. 1 shows the experimental setup and Table S2 gives the associated equipment parameters, inspired by the methods presented in Amon et al.⁹⁵ and Deshpande et al.²⁴. We mount all equipment on a vibration isolation table and enclose the setup in an acrylic chamber wrapped in blackout fabric. The basic principle of DWS is that the interference of coherent laser light within the sample results in a *speckle image* representing the 3-D wavefield incident on the 2-D plane of a camera sensor^{95,96}. The speckles change when non-affine motions occur within the sample, detectable from a change in the autocorrelation of two images separated by a lag time of interest^{95,96}. Non-affine motion results in autocorrelation values lower than the noise floor (0.95), measured from a stationary sample of the same grains glued onto a 3-D printed slab. Using our experimental set-up, we can detect local rearrangement events (LREs) within ~ 20 grain diameters from the borosilicate glass at the front of our DWS sample container (Fig. 1).

Starting from freshly-deposited samples with the prescribed feed rate, we record laser speckle images at 1 Hz. To calculate non-affine strains from the speckle images, we first create down-sampled images where we average the laser light intensities over 10 pixels (metapixels)^{24,95,96} to reduce noise while maintaining a relatively high spatial resolution. Next, we calculate a normalized autocorrelation function $G(t, t + \tau)$ on the metapixel images:

$$G(t, t + \tau) = \frac{\langle I_{t+\tau} \rangle - \langle I_t \rangle \langle I_{t+\tau} \rangle}{\sqrt{\langle I_t^2 \rangle - \langle I_t \rangle^2} \sqrt{\langle I_{t+\tau}^2 \rangle - \langle I_{t+\tau} \rangle^2}}, \quad (11)$$

where t is current time and τ represents a lag time of interest^{95,96}. $G(t, t + \tau) \approx \exp[-c(\varepsilon + \psi)]$, where ψ represents contributions from random noise, and $c = 8\pi \frac{\sqrt{0.4I^*}}{\lambda}$ is a constant proportional to the wavelength λ and the mean free path of the laser light I^* estimated from simulations assuming Mie scattering^{95,96}. Noise contributions are assumed to de-correlate over time^{95,96}, enabling us to calculate the mean $G(t, t + \tau)$ for $\tau = 1$ s, denoted g_1 . Assuming zero strain in the out-of-plane direction z , incompressibility, and that the local strain tensor is coaxial with the stress field (primarily gravity), the longitudinal strain component ε_{xx} can then be expressed as $\varepsilon \approx -\frac{\ln(g_1)}{c}$ ^{95,96}.

Data availability statement

Readers can find all data analysis from this study on the Zenodo repository dedicated to this project⁹⁷.

Code availability statement

Readers can find all the codes used for data analysis and plotting in this study at the Zenodo repository dedicated to this project⁹⁷.

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570 RK: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Review & Editing, Visualization.
 571 VW: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Review & Editing, Supervision,
 572 Project administration, Funding acquisition. EG: Investigation, Writing - Review & Editing. KED: Investigation, Methodology,
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 574 Investigation, Writing - Review & Editing.

575 Competing interests statement

576 The authors declare no competing interests.

Supporting Information for “Fabric and strain analyses support a unified framework for sediment deposition, relaxation, and glass formation

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Summary

This Supporting Information (SI) describes the methods and results for fabric analyses, error analyses, isolated pore analyses, and strain analyses. This SI also contains 14 supporting figures and 3 supporting tables. The figures present supplementary results for local volume fraction ϕ_L (Figs. S1–S2), coordination number Z (Fig. S3), pore volume V_{po} (Figs. S4–S6), contact vector orientations (Fig. S7), physical properties errors (Fig. S8), V_{po} distribution fits (Figs. S9–S11), pore aspect ratio α (Figs. S13–S12), and strain ϵ (Fig. S14) analyses. Specifically, we report the first four statistical moments and probability density functions (PDFs) of the isolated pore volume (V_{po}) and aspect ratio (α). We also present the $I_{i,po}$ clustering analysis of V_{po} and compare the complementary cumulative distribution function (CCDF) of V_{po} with exponential, stretched exponential, power law, and lognormal fits. In addition, we provide the PDFs of Z , V_{po} , and α for all samples (S1–S6), the changes of $\bar{Z}$, CI , a_r , a_{nr} , and fR associated with varying the local threshold during contact detection refinement, along with histograms and the first four statistical moments of the local volume fraction (ϕ_L) for each sample. Finally, we include stereonets of the contact vector orientations for all grains and the mean strain (ϵ) during the first ~ 10 minutes after deposition, shown in three subplots corresponding to different time intervals within this period. The three supporting tables summarize the PIVLAB processing steps used in our analysis, the acquisition and instrumental parameters we used for our DWS experiments, and the statistical metrics of the distribution fits applied to V_{po} .

Text S1: Image Processing

We use PIVLab functions^{1,2} to calculate the velocities of the falling grains captured by the camera (Fig. 1B). Our region of interest is the area surrounding the flow and no larger than the sample container diameter. Image settings, analysis, and validation choices are listed in Table S1.

Text S2: Fabric analyses

Volume fraction: We calculated the local volume fraction ϕ_L of the grains in the samples³. We computed their histograms and their first four moment statistics Figs. S1–S2). In all samples, the histograms are unimodal and narrow-peaked. The standard deviation of ϕ_L scatters and, in all samples, ϕ_L is strongly left-skewed (skewness < -1.6) and extremely heavy-tailed, with excess kurtosis exceeding 8. These statistics indicate that local pore volume is dominated by many large ϕ_L values and a small number of much smaller ϕ_L values.

Contact fabric: Branch vectors of contacting grains exhibit no clear preference for either inclination or azimuth orientations (Fig. S7). This is unsurprisingly similar to what we observe with the non-rattlers (Fig. 4), which make up roughly 94-89 % of the samples.

Text S3: Error Analyses

We calculated errors for $\bar{Z}$, CI , a_r , a_{nr} , and fR by varying the local threshold value that we use to detect grains in contact (Fig. S8). We varied the local threshold from our scaled decimal Otsu threshold grayscale value by adding 0.01 to 0.08. We see that the choice of local threshold does not affect our interpretations. The probability density functions (PDFs) of the coordination number Z that we show in Fig. S3 are based on the results that use the Otsu threshold to detect contacts.

Text S4: Isolated Pore Analyses

Methods: We identify isolated pores, po , using a three-dimensional 26-connected component analysis (where pixels are connected if they share corners, edges, or faces), then calculate their volumes V_{po} , principal axis lengths, orientations, and shape⁴. We perform the analysis on binary images after using a mask to select our region of interest, reflecting where grains and pores exist in the samples.

We calculate the local Moran's I (see Methods in the main text) for the pore volume $I_{i,V_{po}}$ to assess whether pores of similar volumes cluster in space (Fig. S6). Here, we use a mean $x^* = \bar{V}_{po}$ the mean V_{po} and explore a range of $n = 6$ –10 neighbors. We only present results from $n = 6$ since the results are insensitive to n within the range we explored.

To describe the V_{po} distribution, we compute and plot the complementary cumulative distribution function of the V_{po} for each sample, and compare it to exponential, stretched exponential, power law, and lognormal fits⁵ (see Figs. S9, S10, and S11). We then report five metrics that indicate the goodness of fit in Table S3. The fit test compares the two distributions with each other. The log-likelihood value R indicates how likely one distribution is versus the other in describing the data; here, $R > 0$ indicates that the first distribution provides a more likely fit, while $R < 0$ means the second is more likely to be a better descriptor of the data. For the p-value tests of statistical significance of R , $p \leq 0.05$ indicates that R is significant, $0.05 < p \leq 0.10$ suggests that R is weakly significant, and $p > 0.10$ implies that R is insignificant.

The isolated pore algorithm⁴ provides pore orientations in Euler angles (roll Φ , pitch θ , and yaw ψ), which we then convert to azimuth and inclination. We first convert the Euler angles to radians, then calculate Cartesian components: $x = \cos(\psi)\cos(\theta)$, $y = \sin(\psi)\cos(\theta)$, and $z = -\sin(\theta)$. From this, we calculate the azimuth and inclination. We calculate the pore aspect ratio α as the ratio of each pore's short and long axes.

Pore volume: In all samples, the distribution of the isolated pore volumes V_{po} is right-skewed (skewness > 2.5) and heavy-tailed, with excess kurtosis exceeding 10 Figs. S4–S5. These statistics indicate that pore space is dominated by many small voids and a small number of much larger voids. Among several heavy-tailed models tested (e.g., power law and lognormal), the distributions are best described by a stretched exponential form,

$$P(V_{\text{pore}}) \sim \exp \left[- \left(\frac{V_{\text{pore}}}{V_c} \right)^\beta \right],$$

where V_c is a characteristic pore volume and β is the stretching exponent (Figs. S9–S11; Table S3). Neither β nor V_c exhibits a systematic dependence on E_k , indicating that the statistical structure of the V_{po} distribution remains largely invariant across the range of E_k explored. We likewise find no clear dependence on E_k across the cluster fractions. Increasing n from 6 to 10 did not significantly alter the resulting $I_{i,V_{po}}$ clustering patterns.

Pore shape and orientation: Pore shapes (Fig. S12) are largely insensitive to E_k . The isolated pores are approximately oval, with a mean $\alpha \approx 0.50$ in each sample. The standard deviations of α differ by no more than 0.03 across feed rates (Fig. S12B), indicating that the spread of pore shapes is nearly constant. All α distributions exhibit moderate right-skew (skewness

74 $\approx 0.2\text{--}0.7$; Figs. S12C, S13); this reflects the slight preference for elongated oval pores. Although skewness generally decreases
75 with increasing E_k , feed rate S5 exhibits a higher value that interrupts this otherwise relatively weak trend (Figs. S12C, S12E).
76 While excess kurtosis shows some scatter, all samples are slightly lighter-tailed than a normal distribution, with the excess
77 kurtosis values ranging from -0.02 in S5 to -0.80 in S3 (Fig. S12D). Pore orientations exhibit a consistent sub-vertical
78 ($\sim 60^\circ$) to vertical inclination preference across all samples (Fig. 4C).

80 **Text S5: Post-depositional relaxation dynamics**

81 We conduct the diffusing wave spectroscopy (DWS) experiments and analyses as described in the Methods section of
82 the main text. Table S2 lists the components of the DWS set-up and their associated specifications. These components and
83 specifications were modified from the set-ups presented in Amon et al.⁶ and Deshpande et al.⁷. To further visualize the trends
84 in the relaxation profiles, we present plots of the relaxation profiles at three time ranges: 0–1.5 s, 0.5–3.5 s, and 2.5–10 s in
85 Fig. S14.

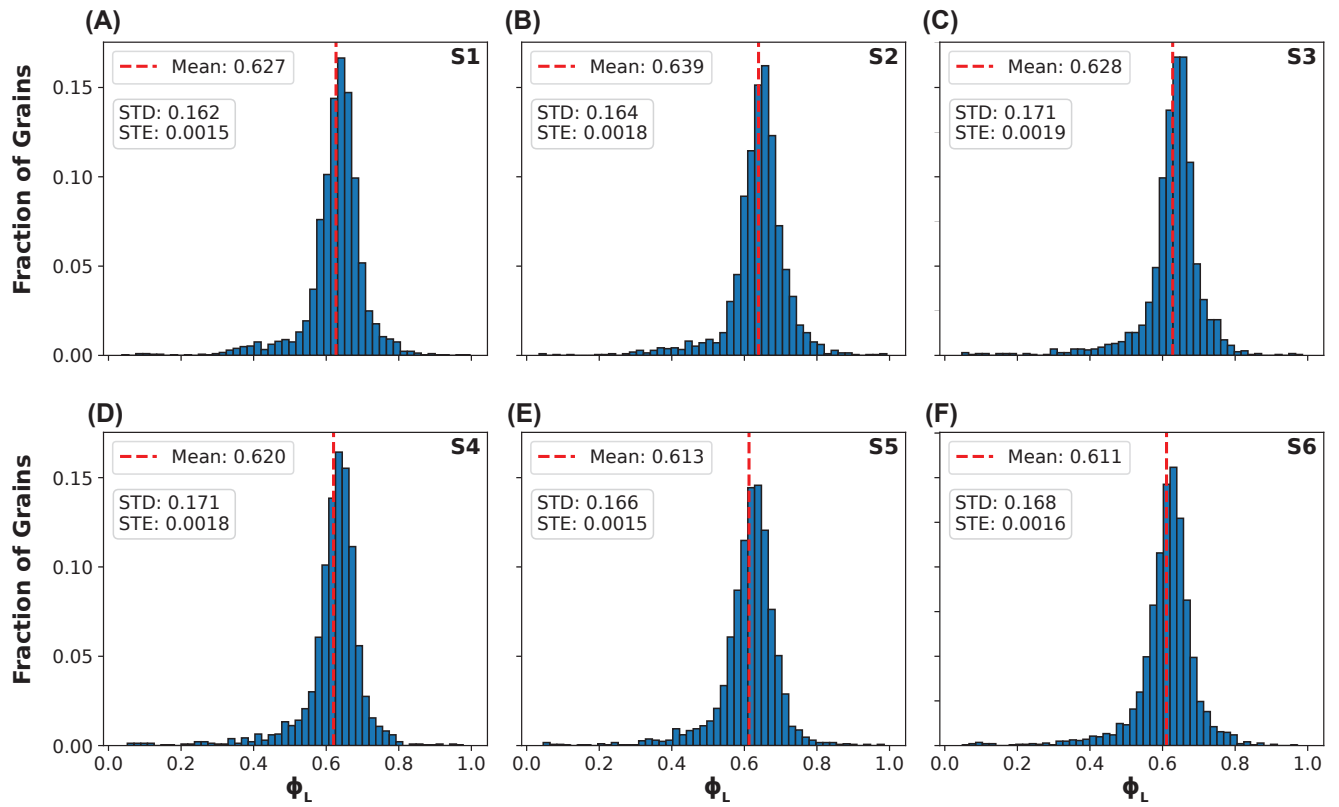


Figure S1. Histograms of the ϕ_L distribution of each sample. Dashed red line is the mean, which we report as ϕ in the main text.

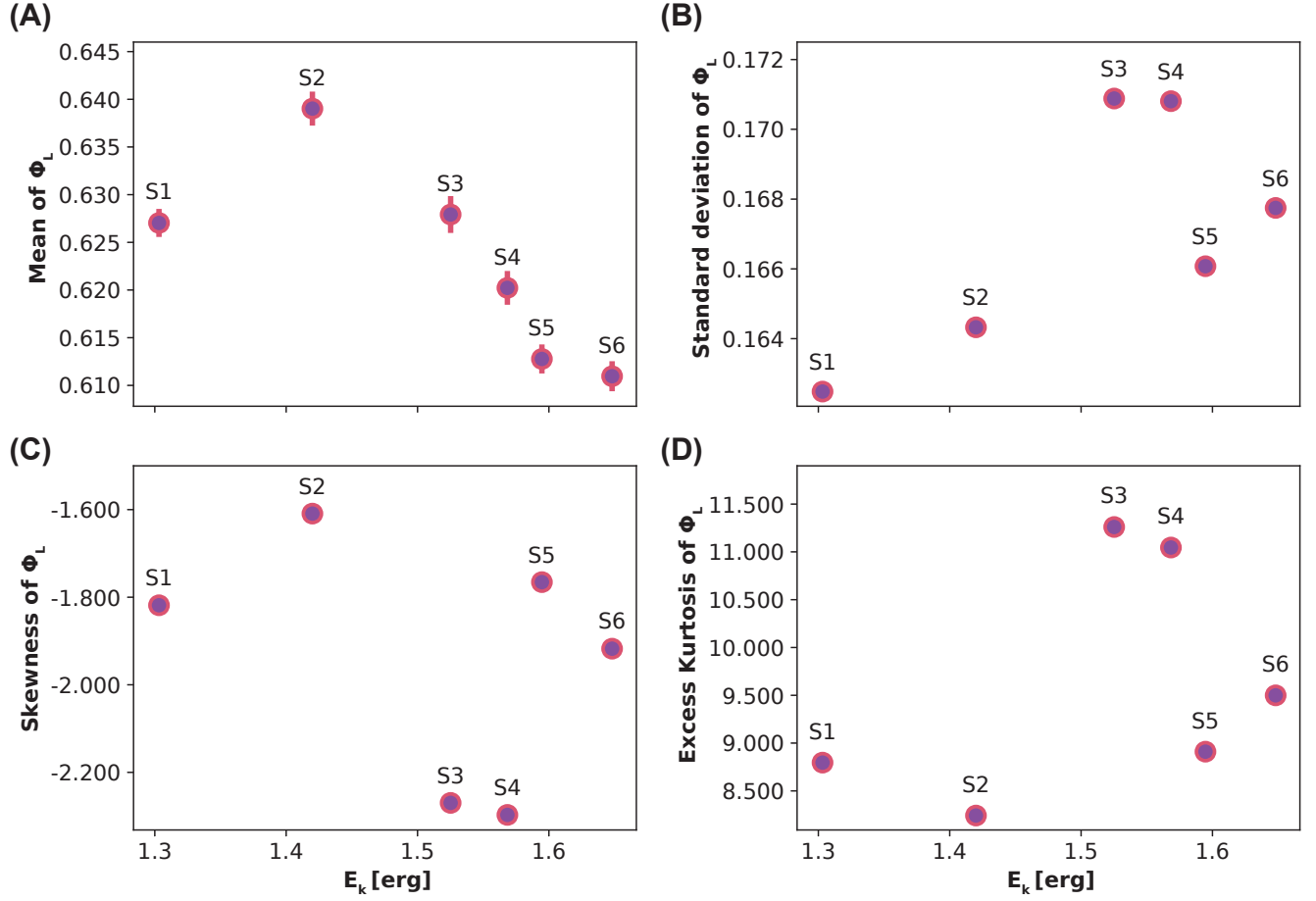


Figure S2. Local volume fraction ϕ_L and its moments as a function of E_k . All moments and the median scatter with E_k . (A) Mean ϕ_L vs E_k . (B) Standard deviation vs E_k . (C) Skewness of ϕ_L vs E_k . (D) Excess kurtosis of ϕ_L vs E_k . Standard errors for E_k are smaller than the marker size.

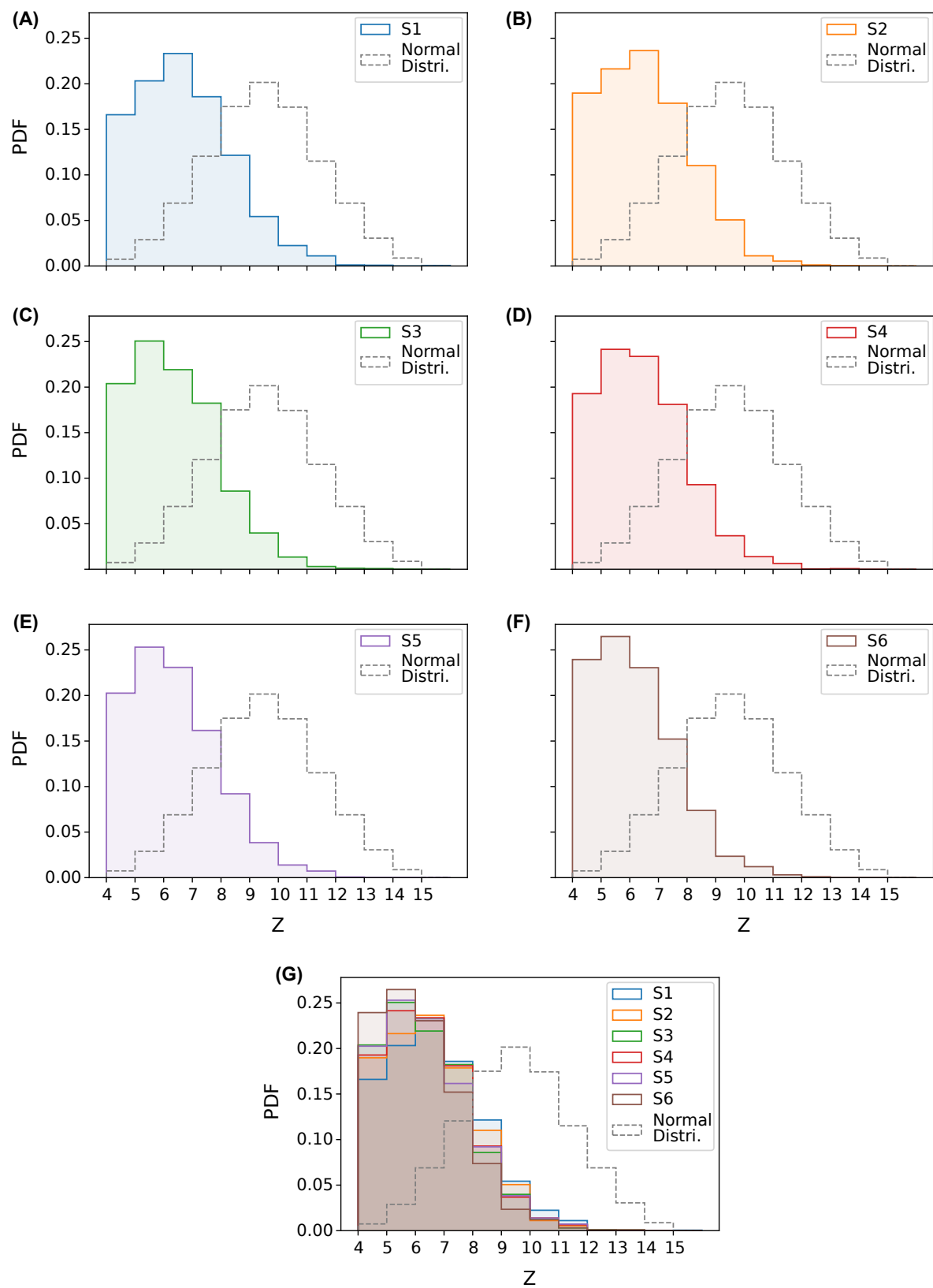


Figure S3. Probability density function (PDF) of coordination number Z .

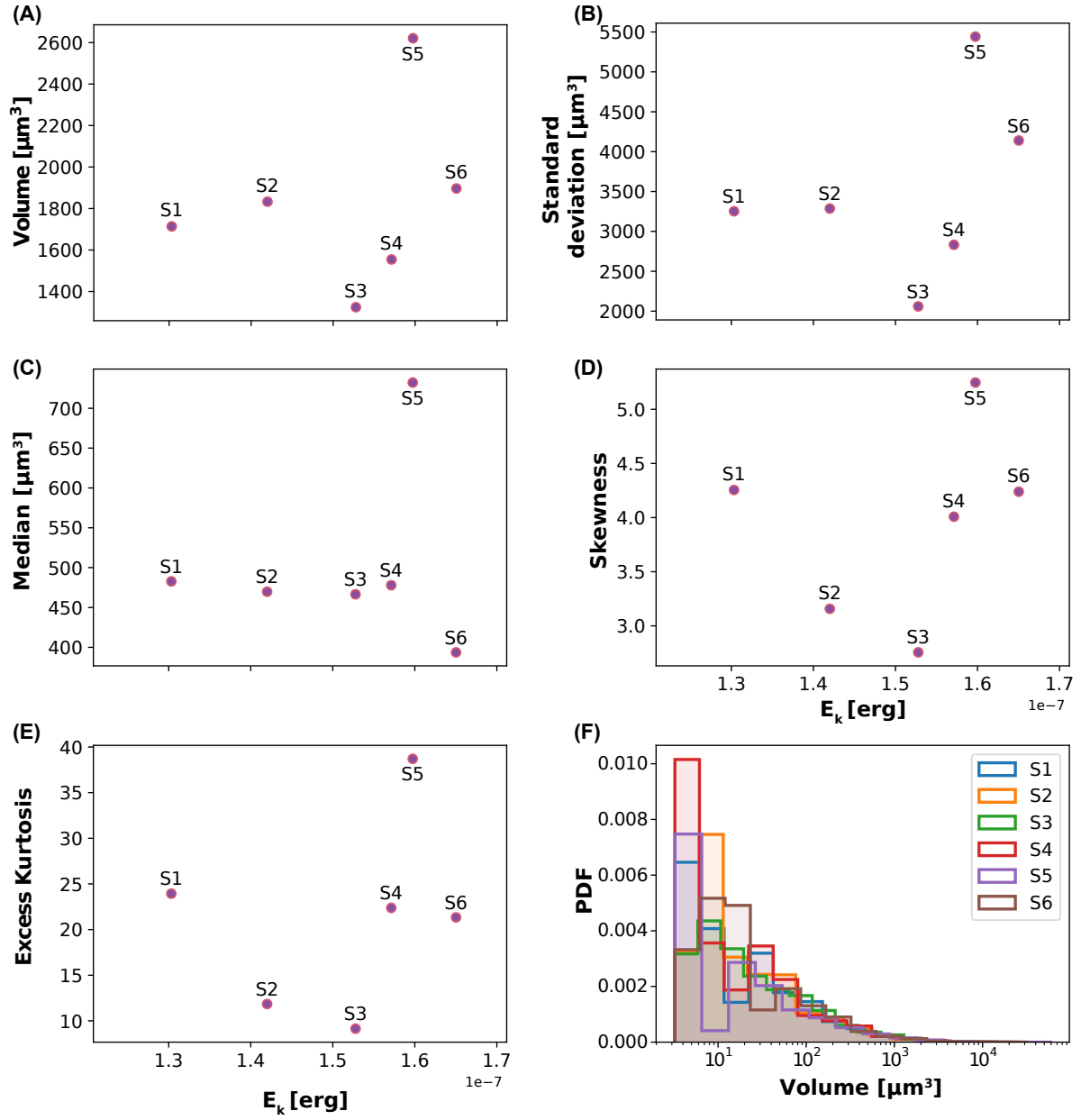


Figure S4. Pore volume V_{po} and its moments as a function of E_k . All moments and the median scatter with E_k . (A) Mean V_{po} vs E_k . (B) Standard deviation vs E_k . (C) Median V_{po} vs E_k . (D) Skewness of V_{po} vs E_k . (E) Excess kurtosis of V_{po} vs E_k . (F) PDF of V_{po} in log-linear space to better show tails of the distribution. Standard errors for E_k are smaller than the marker size.

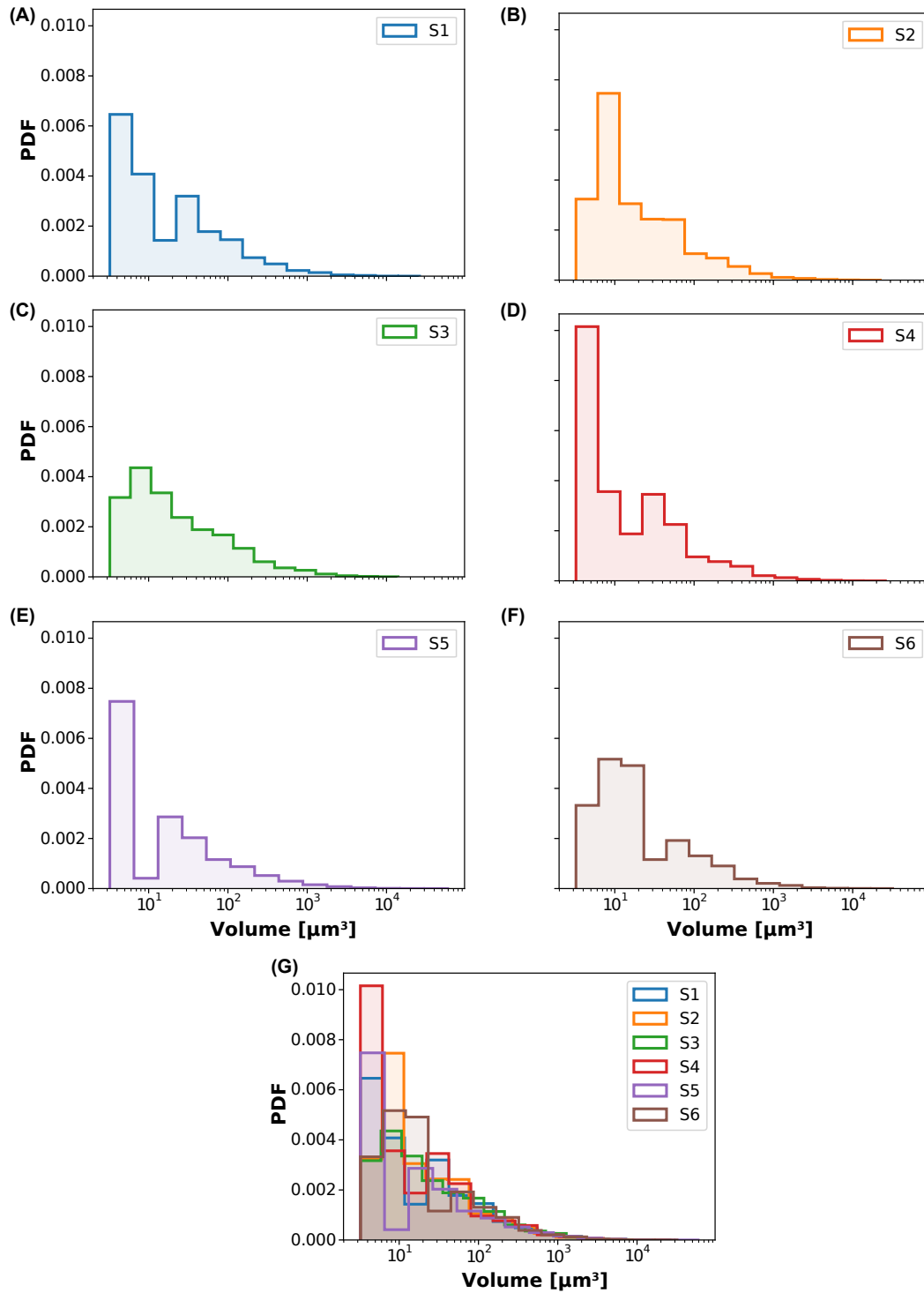


Figure S5. Probability density function (PDF) of pore volume V_{po} for each sample.

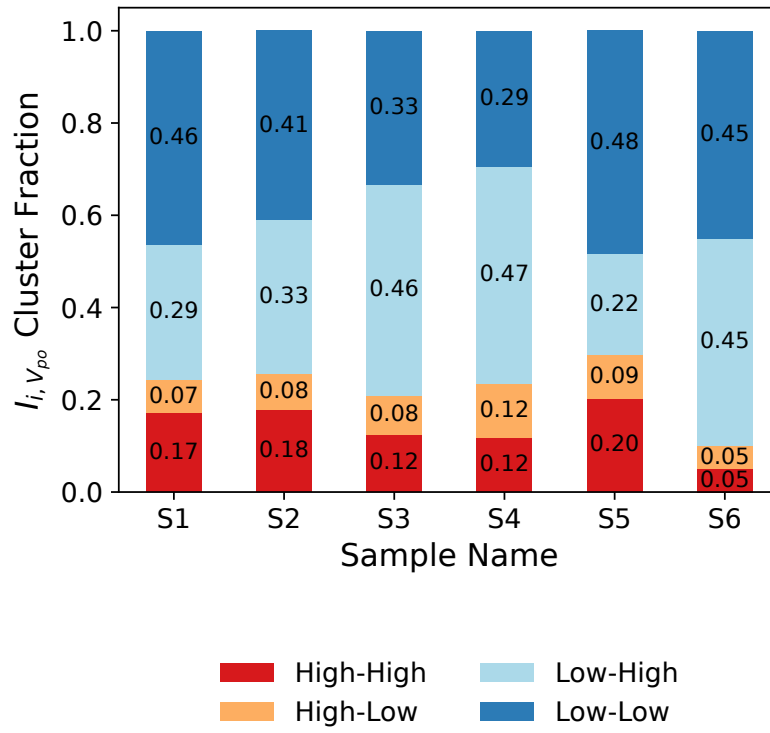


Figure S6. Fraction of the four types of I_i clusters based on V_{po} . $I_{i,V_{po}}$ fractions show no clear dependence on E_K .

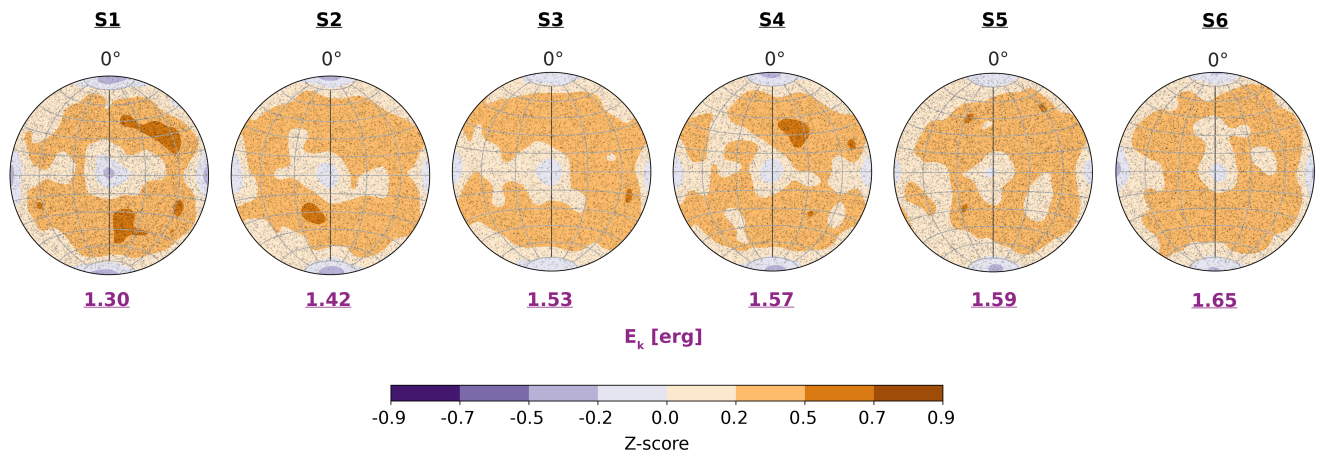


Figure S7. Density-contoured stereonets of the orientations of the contact vectors for all grains. Contours and colors represent the Z-score derived from 500 simulations of random, uniform distributions. In a given area, a positive z-score indicates that the data has a higher density of points than the random distributions, and a negative z-score indicates that the data has a lower density of points than the random distributions. The dark gray vertical line in the middle of each stereonet is vertical (90°) inclination. Contour density method is from Kamb (1959)⁸.

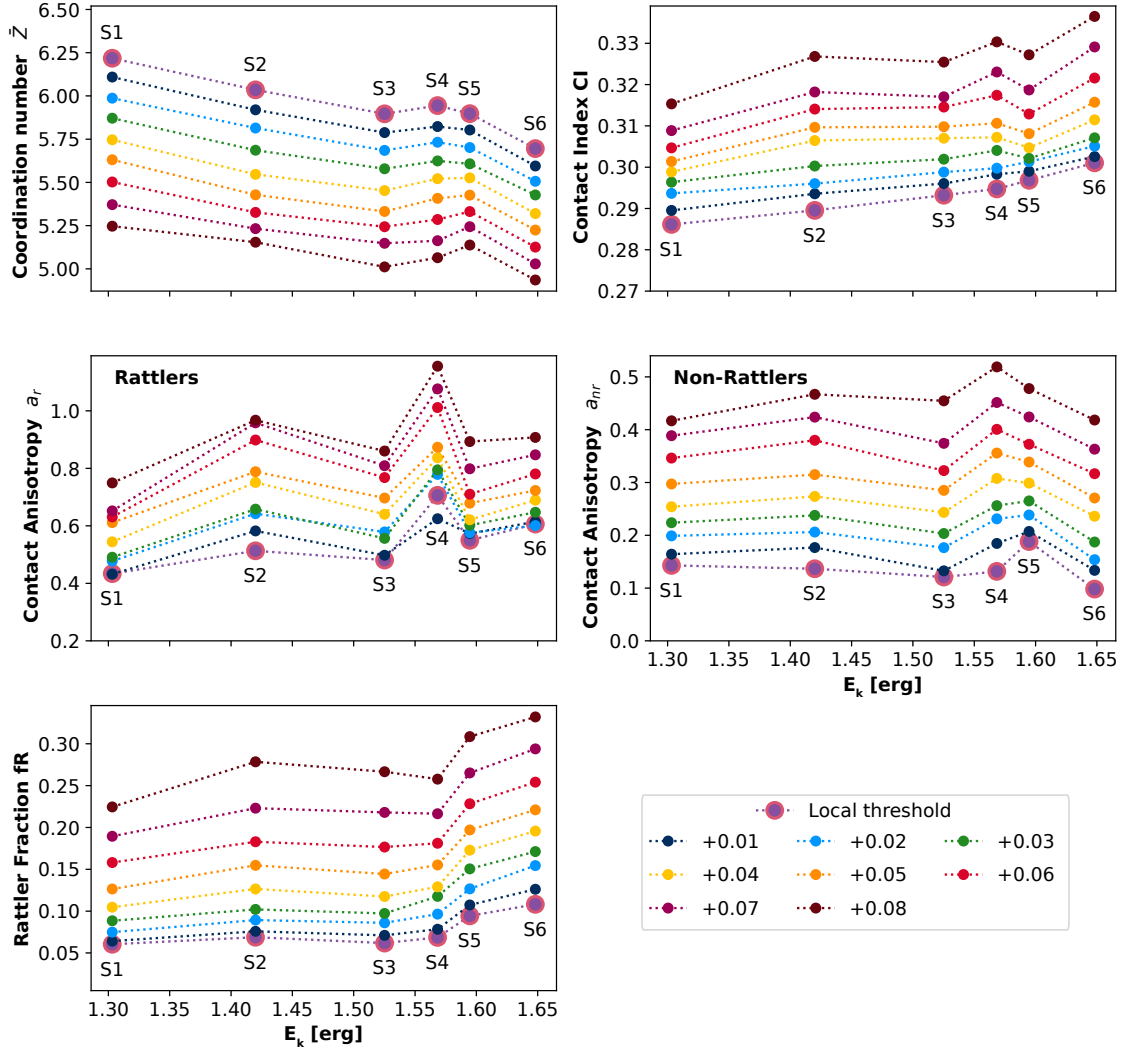


Figure S8. We varied the local threshold that we use to detect grain–grain contacts for coordination number calculations. We normalize the grayscale values between 0 and 1, and set the peaks of the grains and pores to 0.25 and 0.75, respectively. Reported values of Z in the main text are based on the scaled Otsu threshold value that we use to binarize each sample. Here, we detect contacts with the Otsu value, referred to as the local threshold in the figure, as well as values that are 0.01–0.08 larger than the Otsu local threshold value. We then recalculate (A) mean coordination number $\bar{Z}$, (B) contact index CI , (C) rattler fabric anisotropy a_r , (D) non-rattler fabric anisotropy, and (E) rattler fraction f_R to examine the effect of the threshold values for contact detection on any observed trends with E_k . $\bar{Z}$ decreases by a maximum of one based on the choice of local threshold, but the data trends remain largely the same as reported in the main text. Standard errors for E_k are smaller than the marker size.

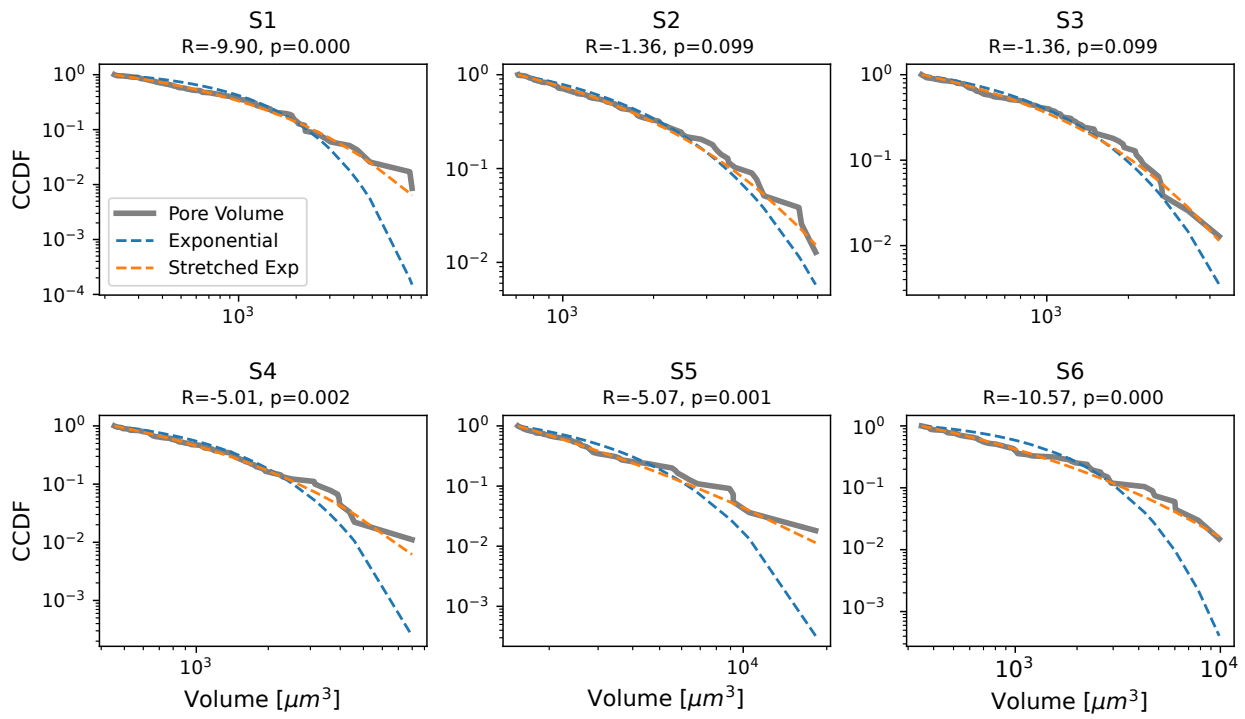


Figure S9. Complementary cumulative distribution function (CCDF) of V_{po} compared against an exponential and stretched exponential fits.

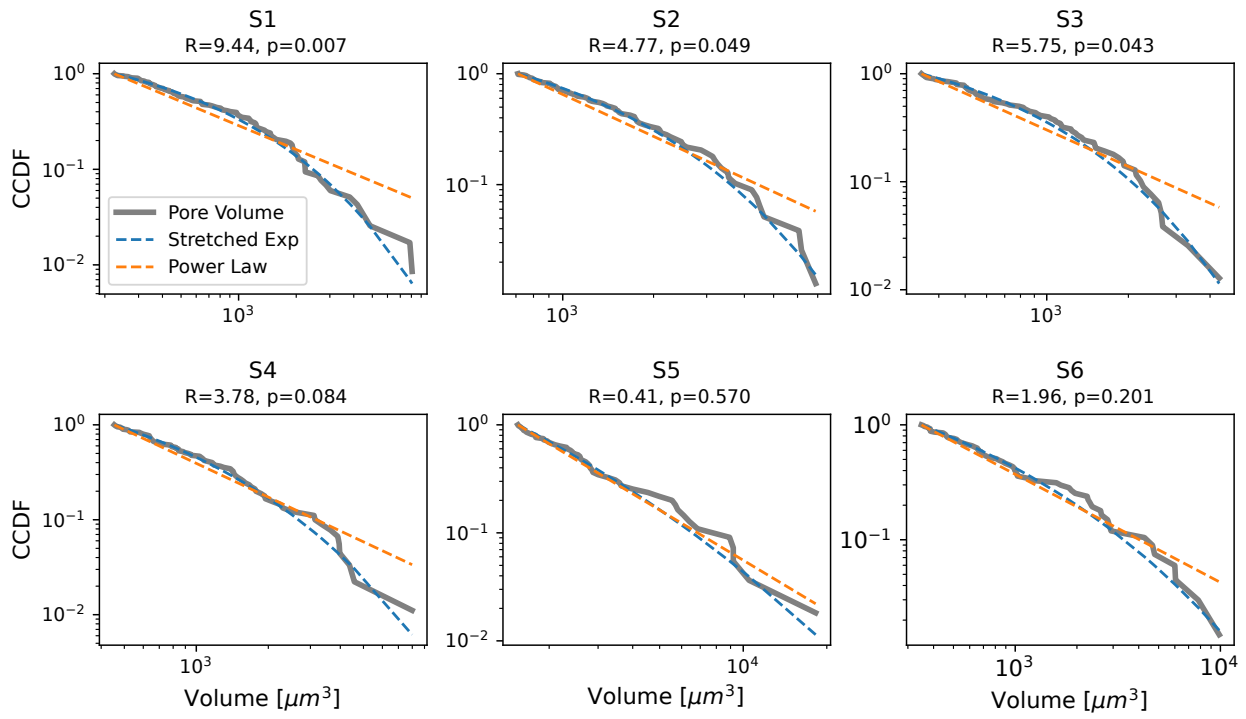


Figure S10. Complementary cumulative distribution function (CCDF) of V_{po} compared to the stretched exponential and power law distributions.

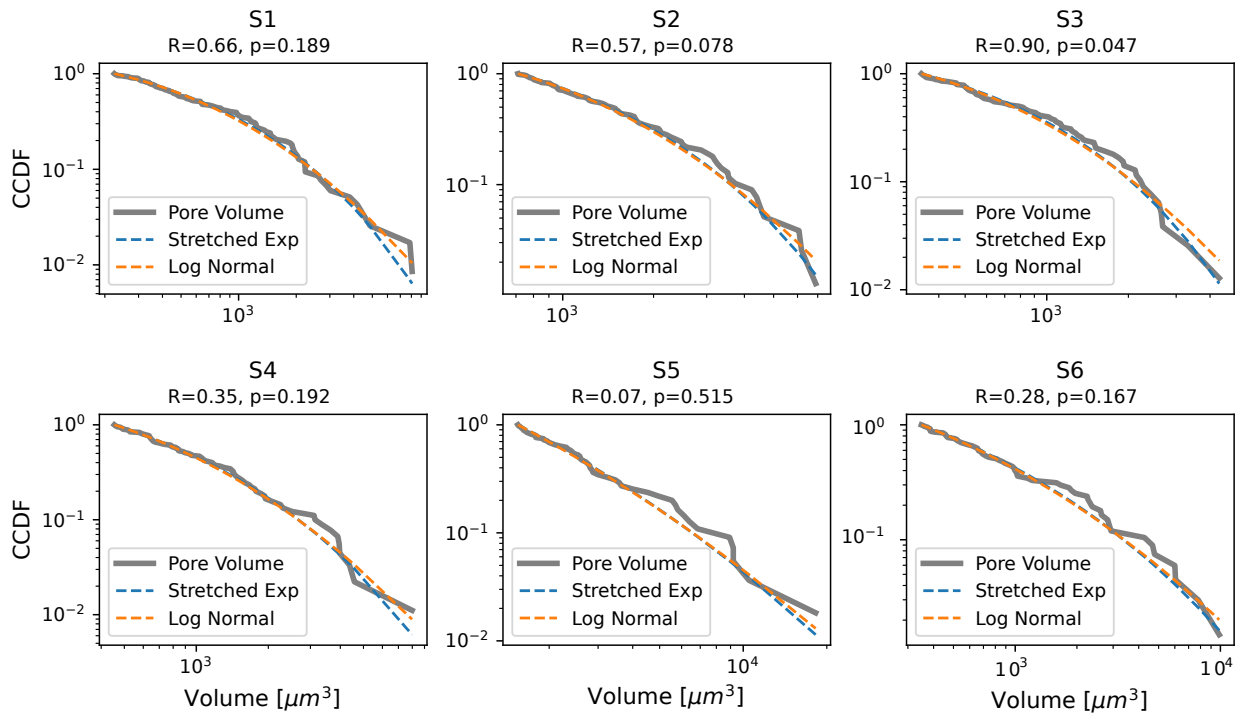


Figure S11. Complementary cumulative distribution function (CCDF) of V_{po} compared to the stretched exponential and lognormal distributions.

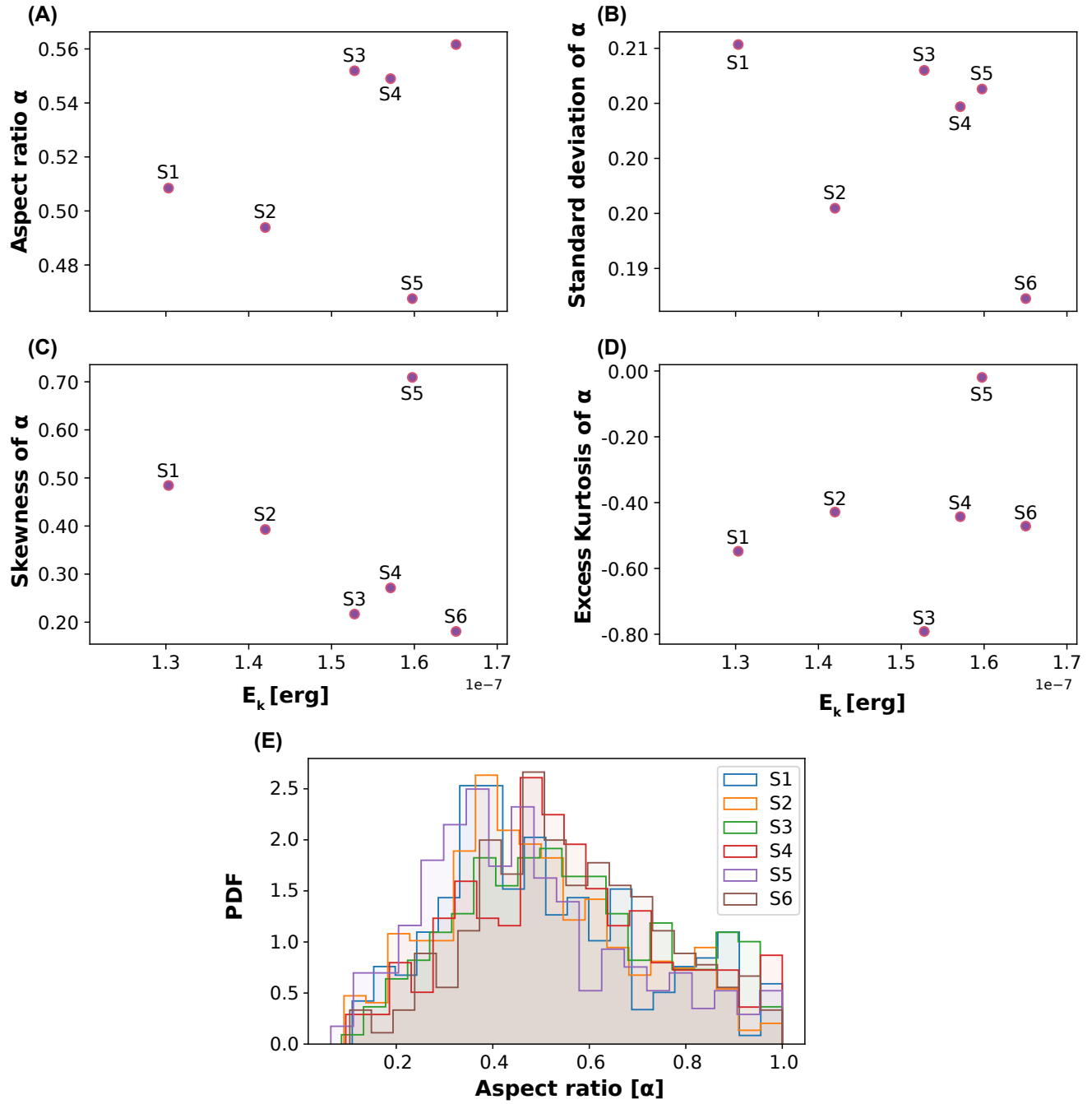


Figure S12. Pore aspect ratio α and its moments as a function of E_k . (A) Mean α versus E_k , α scatters with E_k . (B) Standard deviation of α scatters with E_k . (C) Skewness of α decreases non-monotonically with E_k . (D) Excess kurtosis of α scatters with E_k .

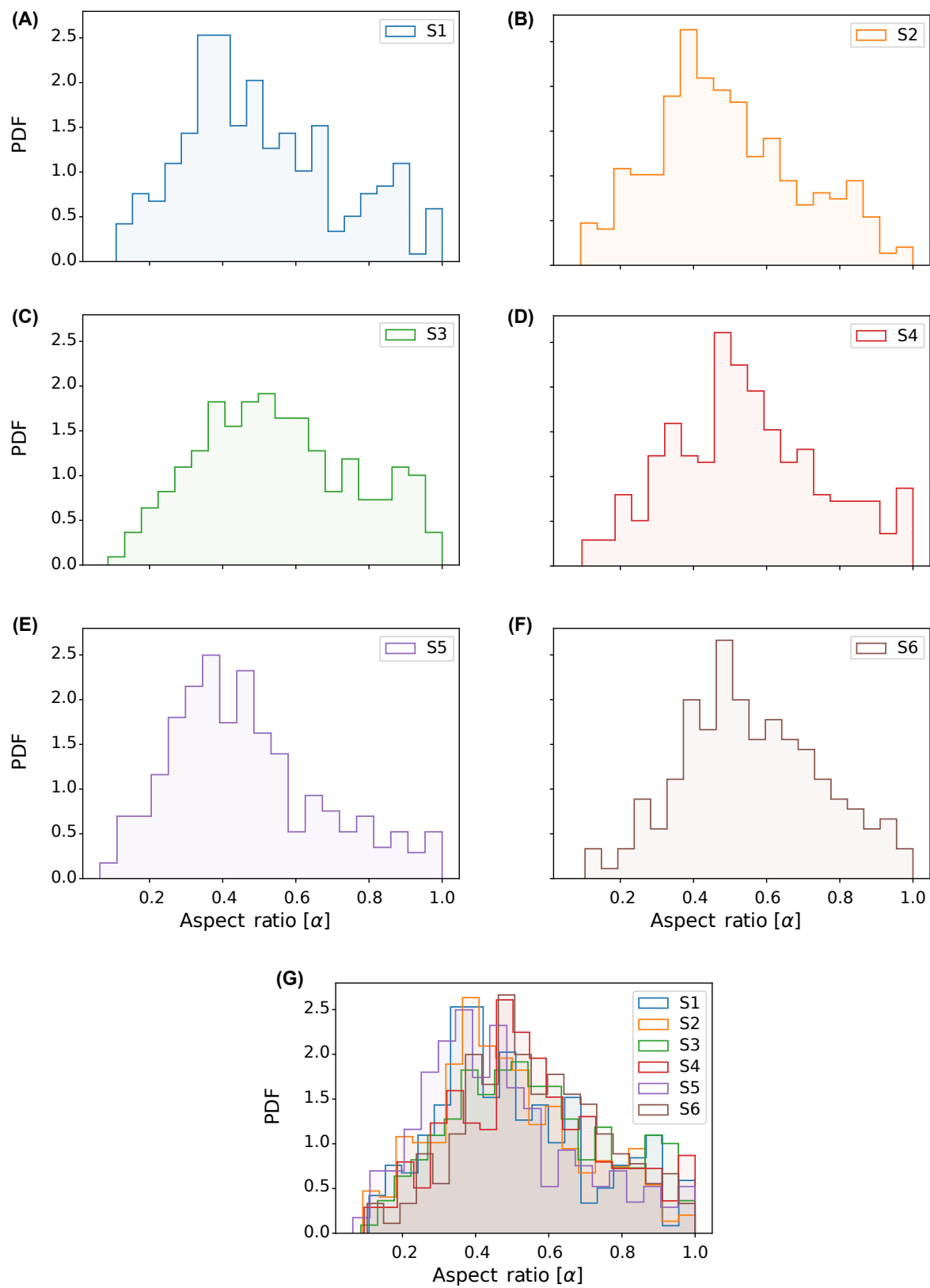


Figure S13. Probability density function (PDF) of pore aspect ratio α .

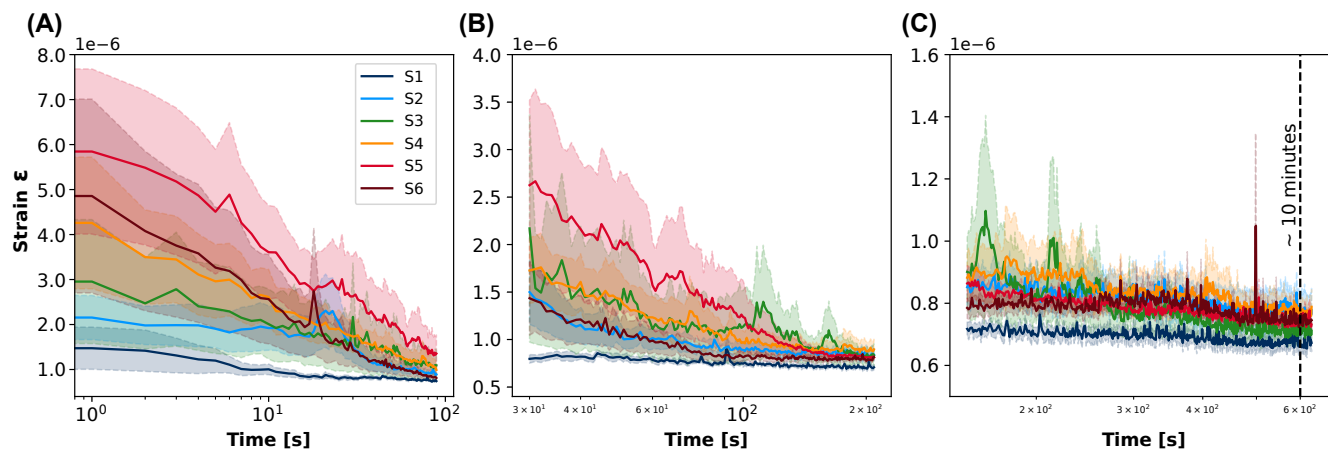


Figure S14. Mean strain ϵ of each sample within ~ 10 minutes of deposition, captured using diffusing wave spectroscopy measurements. The shaded regions represent the standard error over five runs. (A) 0–1.5 s, (B) 0.5–3.5 s, (C) 2.5–10 s.

Table S1. Parameters that we use during our particle image velocimetry (PIV) analyses, implemented using PIVLAB^{1,2}.

Image Setting	Analysis	Validation
Image Pre-processing: • Enabled intensity capping	PIV Settings: • Ensemble multipass FFT – Pass 1: 64 px, 32 px step – Pass 2: 32 px, 16 px step • Gauss 2x3-point sub-pixel estimator • Disabled auto-correlation • High correlation robustness	Velocity Based Validation: • Local median filter, threshold = 3.

Table S2. Optical components and associated specifications that we use to conduct the diffusing wave spectroscopy (DWS) experiments.

Component	Specification
Measurement geometry	Backscatter
Laser	He–Ne, coherent, 633 nm, 5 mW
Initial beam diameter	0.8 mm
Beam expander	10 $\times$; c in Fig. 1A
Holographic diffuser	30 $^\circ$ half-angle, top-hat profile; b in Fig. 1A
Illuminated area	5 cm diameter circle
Collimating lens	75 mm focal length; a in Fig. 1A
Polarizer	Linear, single polarization recorded; d in Fig. 1A
Bandpass filter	633 $\pm$ 5 nm; e in Fig. 1A
Camera	Ximea xiQ MQ022MG-CM (CMOS)
Camera sensor resolution	2048 $\times$ 1088 pixels
Camera pixel size	5.5 μ m
Camera aperture	$f/22$
Camera frame rate	1 Hz
Mean speckle size	2.9 pixels
Vibration isolation	8 inch thick optical table
Environment isolation	Acrylic chamber; blackout fabric enclosure

Table S3. Statistics from distribution fit tests for pore volume. We compare three models: (1) exponential (Exp) vs stretched exponential (StrExp), (2) stretched exponential vs power law (PwrLaw), and (3) stretched exponential vs lognormal (Lognrml).

Fit Test	Log Likelihood (<i>R</i>)	p-value (<i>p</i>)	Fit Choice	Fit Significance
Exp - StrExp	-9.90	0.000009	StrExp	Sig
	-1.36	0.099	StrExp	Weak Sig
	-1.36	0.099	StrExp	Weak Sig
	-5.01	0.002	StrExp	Sig
	-5.07	0.001	StrExp	Sig
	-10.57	0.000004	StrExp	Sig
StrExp - PwrLaw	9.44	0.007	StrExp	Sig
	4.77	0.049	StrExp	Sig
	5.75	0.043	StrExp	Sig
	3.78	0.084	StrExp	Weak Sig
	0.41	0.570	StrExp	No Sig
	1.96	0.201	StrExp	No Sig
StrExp - Lognrml	0.665	0.189	StrExp	No Sig
	0.567	0.078	StrExp	Weak Sig
	0.899	0.047	StrExp	Sig
	0.345	0.192	StrExp	No Sig
	0.656	0.515	StrExp	No Sig
	0.284	0.167	StrExp	No Sig

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