

Ubiquitous mechanism of creep-quake cycles in porous media

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The degradation of porous media can trigger devastating events, from sinkhole formation to ice-shelf breakouts. In a recent study, regularly recurring creep-quake collapse cycles were identified in cereals, whose progression was related to partial saturation. This Letter reveals such patterns in other materials, including sand and ice, but crucially, we demonstrate that they do not necessitate partial saturation. Conversely, we experimentally and theoretically show how the mechanism underpinning the creep-quake collapse cycles can develop in any porous medium, as long as it is simultaneously subjected to compression and a nonuniform degradation field, let that be a hydraulic, thermal, or chemical field. Our results highlight the ubiquity of creep-quake collapse cycles and the importance of the underlying degradation processes that activate this mechanism in any porous medium. Given the vast interest in porous media, this understanding is anticipated to have significant implications in the agricultural, pharmaceutical, and environmental sciences.

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We quickly learn that ice, salt, cereal, and sand do not look or taste the same. They further differ in how they crumble when pressed and how they behave when soaked in water or taken out of a freezer. One would commonly study such changes in each material separately, but there is much to gain in identifying universal traits they might share, as these could facilitate the transfer of ideas and understanding from one material to another. Indeed, despite their differences, all these materials belong to the class of porous media, having a solid skeleton, as well as pores that can retain or transfer fluids. Most importantly, their degradation causes many problems in geosciences, for example, where chemical dissolution instigates sinkhole formation [1,2], and global warming accelerates ice-shelf melting [3,4]. The degradation of porous media is also relevant in industry, where their properties are regularly manipulated through external thermal, hydraulic, or chemical fields, for example, during food and drug processing [5–8].

Previous work on puffed rice cereal, a seemingly inconsequential material, revealed a collapse pattern that develops under simultaneous load and partial water saturation [9]. The pattern is characterized by regularly recurring compaction events, coined “ricequakes,” interluded by creep deformation. Ricequakes originate in a highly degraded zone within the medium and result in [9] (1) distinct acoustic emissions; (2) drops in applied servo-controlled load and rapid associated collapse of the sample; and (3) the formation of layers of compacted material, similar to those found in rocks [10–14]. Several studies have observed a rich array of collapse patterns

in the past [15–19], focusing on cycles of creep, collapse, and associated acoustic emissions, arising from the continuously imposed deformation of the porous materials. However, the collapse mechanism in Ref. [9] is uniquely different, with the puffed rice porous material being degraded by an external agent through partial water saturation, eventually leading to the collapse of the material.

Hence, the identification of recurring ricequakes and creep, or more broadly “creep-quake cycles,” begs to question the possibility of similar patterns in other porous media under degradation fields different from partial saturation.

To study this question, we developed an experimental campaign consisting of five distinct testing configurations on four different porous materials: puffed rice cereal, calcareous sand, rock salt, and crushed ice. All these materials were simultaneously subjected to constant compressive load and a degrading agent specific to their physical or chemical properties (Fig. 1). Hence, water was used to degrade puffed rice and salt through absorption and dissolution, respectively; acetic acid was used to chemically react with calcareous sand; and crushed ice was melted by applying a heat source at the base of the sample.

As shown in Fig. 1, the samples were placed in an acrylic tube between a porous plate and a porous loading piston to allow for liquid transfer. All the samples were carefully prepared to minimize degradation prior to testing, with different strategies depending on the material and the degrading agent, as detailed in the Supplemental Material [20]. The initial height of the samples H_0 was at least 1.5 times their width D .

Once prepared, the samples were slowly loaded to a nominally constant load using a servo-controller, except for the crushed ice. The strain and strain rates during quakes in the crushed ice exceeded the ability of the servo-controller to maintain the piston in contact with the top of the material column, so a dead weight setup was preferred for this experiment. The corresponding degrading agents were then introduced and pictures were taken through a narrow window along the central axis of the tube, from which spatiotemporal

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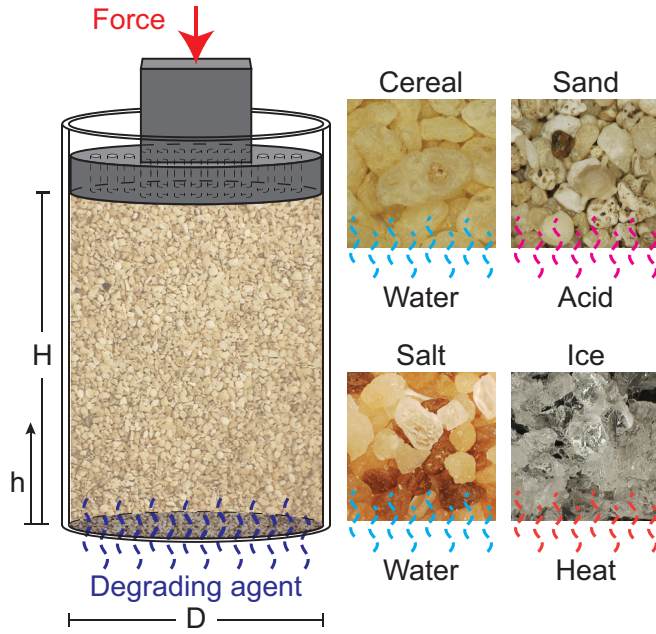


FIG. 1. Experimental setup on various uniaxially compressed materials and degrading agents. Experiments include puffed rice degraded by water, calcareous sand by acid, rock salt by water, and crushed ice by heat.

plots were generated to visualize sample deformations over time and depth (Fig. 2). In order to accommodate for the specific properties of each tested material, the introduction of degrading agent varied slightly across the five different experiments. For the puffed rice, a known volume of water was injected from under the sample at the start and it was not renewed. The sand samples were injected with an acidic solution at a constant rate via four equally spaced inlets for the partially saturated setting and from under the bottom plate for the fully saturated one. Similar to the latter, water was injected through the bottom of the salt samples at a constant rate. Finally, the crushed ice was melted with a heat source placed under the bottom plate. For further technical details on the experiments, material properties and handling, sample preparation, and the application of degrading agents, see the Supplemental Material [20].

Remarkably, all the spatiotemporal plots in Fig. 2 reveal recurring sudden collapses of the porous structure with creep deformation periods in between, as detected originally in soaked puffed rice [9]. These creep-quake cycles are confirmed in Fig. 3(a), which shows the nominal strain $\varepsilon = 1 - H/H_0$ over normalized time $\varepsilon_0 t$ curves, where t is time, H is the current sample height, and ε_0 is the measured nominal initial strain rate in each experiment [Fig. 3(b)]. This normalization was used to allow direct comparison of materials with

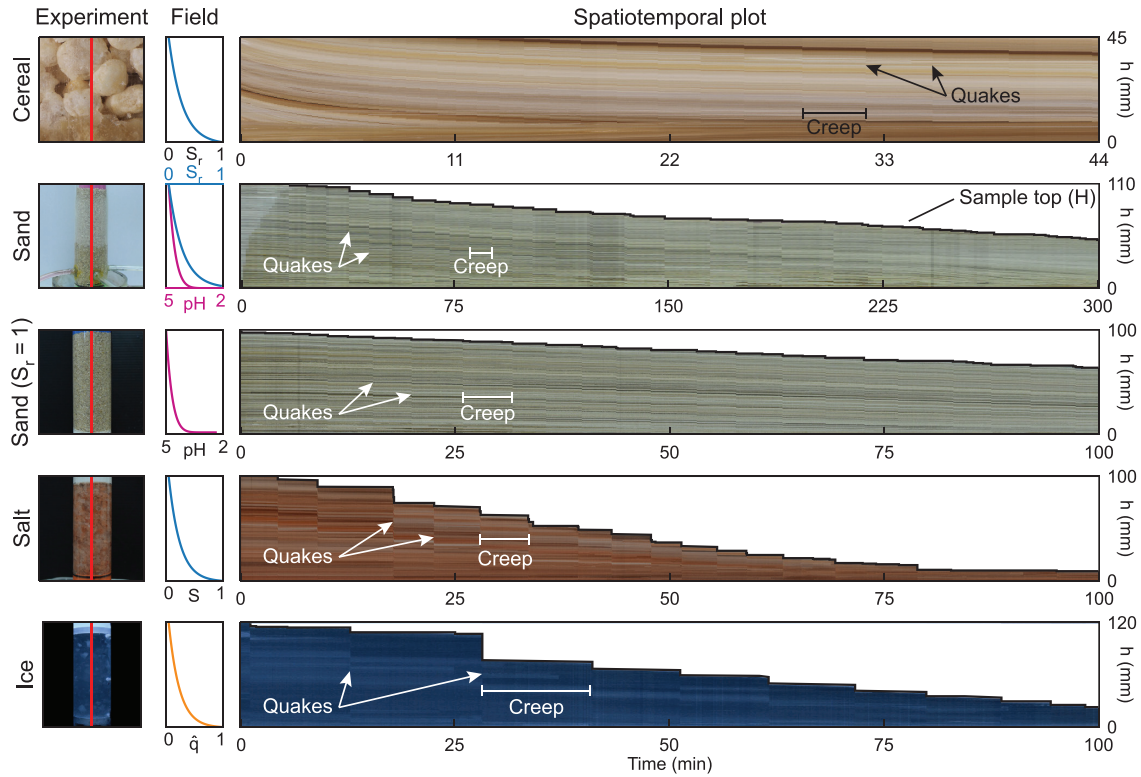


FIG. 2. Ubiquity of the creep-quake cycles. Materials from top to bottom: puffed rice under water saturation field S_r [9]; calcareous sand in combined fields of water saturation S_r and pH induced by an acetic acid solution, with pH = 2.4 at the bottom; calcareous sand fully saturated in an acetic acid solution (pH = 2.4 at the bottom); rock salt fully saturated in water under solubility field S ; and crushed ice fully saturated in brine under heat field imposed by a heat source at the bottom, where $\hat{q}$ is the heat available for ice melting normalized by the heat input. From left to right: first column shows pictures of each experiment; second column schematically shows the corresponding degradation fields; and third column presents spatiotemporal plots of the pixels located under the red lines on the left images, which highlight the recurrence of the creep-quake behavior. The vertical steps observed in the spatiotemporal plots are signature of quake events.

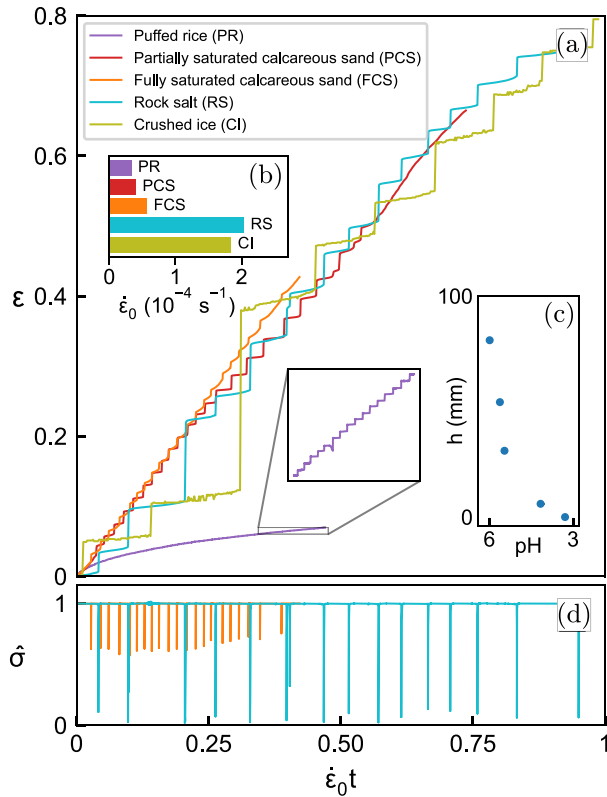


FIG. 3. (a) Strain ϵ versus normalized time $\epsilon_0 t$. (b) Nominal initial strain rate ϵ_0 (slope of the strain-time curve from $t = 0$ to the fifth quake of each data set). (c) pH measurements taken from the side of the test tube during a 1 ml/min flow rate experiment on a fully saturated calcareous sand sample, averaged over 1 h. (d) Stress drops in the fully saturated sand (in orange) and rock salt (in cyan) experiments, where $\hat{\sigma}$ is the applied stress normalized by target stress (4.35 and 0.54 MPa, respectively).

very different degradation rates. The deformation patterns are notably similar in all samples, with the puffed rice curve deviating from the trend, as it is the only experiment where the degrading agent is injected once initially instead of being renewed over time. This difference leads to a significant slowdown of the creep-quake cycles as the degradation wears off. Further noteworthy similarities include loud bursts of sound accompanying quakes in all the experiments, as well as load drops in the servo-controlled tests, two examples of which are shown in Fig. 3(d), where the quakes are clearly visible. The stress drops a significant fraction of the applied load during a quake, well above the fluctuations from the servo-controlled load, and in a time scale significantly shorter than the response time of the control. Incidentally, this prevents a detailed analysis of the material dynamic during a quake event, due to their speed and the interaction with the servo-control during the load recovery.

While on the surface the observed patterns of compactions are reminiscent of classical “stick-slip” behavior, the mechanism leading to the creep-quake instability is entirely different. In most stick-slip models, there is a constant injection of mechanical work, resisted by an opposite force (typically friction), up to a point of instability, which causes sudden motion to occur. Such models have proven effective

in representing the physics of fault slips and earthquakes [21–25], where the work is provided by the movement of the Earth’s crust. However, stick-slip models are not an appropriate tool to capture the physics that drive the creep-quake cycles in this Letter. During the creep phase, while the medium remains under load, the contribution of the mechanical energy is small, and the energy balance is entirely dominated by the chemical energy. This can be shown, for example, in the degradation of the calcareous sand. The main chemical reaction is $\text{CaCO}_3 + 2\text{H}^+ \rightleftharpoons \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O}$, which has an enthalpy energy of -17.7 kJ/mol [26]. A typical creep phase lasts around 5 min, corresponding to an injection of 0.06 mol of acetic acid, and therefore a total chemical energy liberated of around 1180 J. During the same creep phase, the column deforms at most 1 mm under a 4 kN load, corresponding to a mechanical work of 4 J, two orders of magnitude lower than the chemical contribution. Consequently, the motion is driven by the continuous degradation of the porous medium, leading to its eventual collapse, and the minor injection of mechanical work is a by-product of the chemical reaction. In the absence of chemical degradation, no mechanical work is injected. The “creep-quake” instability observed is therefore a type of chemo-mechanical instability, rather than a purely mechanical instability like the archetypal “stick-slip.”

Despite the diversity of the studied materials, they are all porous media, and thus, carry a length scale related to their typical pore size. Similarly, the degrading agents are vastly different, but their reactions with their corresponding porous media all result in material weakening (softening) by either a reduction of mass (melting/dissolving) or a softening of the material matrix (water absorption). Furthermore, their presence is always nonuniform within the medium due to capillarity in the partially saturated samples, flow rate and chemical kinematics in the samples saturated in acidic or salty water, and heat transfer. In all cases, these different physical mechanisms result in the development of a local gradient that is steepest close to the bottom of the sample, as illustrated schematically in Fig. 2, second column. In fact, such a nonuniform field was measured directly in a calcareous sand experiment under full saturation in acidic solution, as shown by the pH profile in Fig. 3(c). Note that although localized collapse events were previously found in ice even under uniform melting, these occurred sporadically and anywhere within the samples [27], which we further reproduced and included in our Supplemental Material [20]. Unlike these uniform melting experiments, the nonuniform experiments in Fig. 2 resulted in localized, more frequent quakes, as well as accelerated creep deformations. Finally, we found that without the applied pressure, no quake develop. An example of the transition between no quake appearing at low applied pressures to quakes emerging once sufficient pressure is applied to a sample can be seen in the Supplemental Material [20] and in Ref. [28].

These observations suggest that there are three key ingredients behind the creep-quake cycles: (1) the intrinsic length scale of the pores; (2) the nonuniformity of the degrading agent field; and (3) the applied pressure.

In the absence of an internal length scale, it is clear that recurring quakes could not happen. For example, a solid block

with no pores can compress and reduce in size, but has no available space for sudden collapses to occur. Conversely, a material that is mainly one large pore (an empty shell) can collapse only once.

Second, quakes occur when a localized instability initiates the sudden collapse of a degraded zone in the material. This requires the material to have inhomogeneous degradation levels across its height, a requirement that is satisfied by the nonuniformity of the degrading agent. In addition, material at the same height will have a similar level of degradation, promoting the concurrent collapse along a horizontal plane once a local region of the material breaks. As collapse occurs, less degraded material is brought into the region of higher degradation, leading to the cycle of creep and collapse. Meanwhile, the gradient of the degrading agent is maintained by the material consuming the agent as it undergoes degradation.

Finally, the applied pressure is needed, as lower pressures allows the material matrix rearrange continuously rather than develop a collapsing instability.

To further explain the creep-quake cycle behavior and generalize the mechanism behind it, we developed a simple theoretical model with these three factors at its core. The model extends a previous model developed specifically for puffed rice [9]. In both cases, a one-dimensional array of degradable elasto-brittle carriages, representative of solid-pore units, is set to sustain a uniform compressive stress σ under a steady, nonuniform degradation field [Fig. 4(a)]. Unlike the previous model, here the model is not limited to porous media weakened by capillary rise, so that the emergence of the creep-quake phenomenon could be explained most broadly. Additionally, unlike soaked puffed rice [9], in the more general cases, the solid medium can recover a finite strength after localized failure due to pore closure and rearrangement. To model this, carriages are let to both degrade continuously and collapse multiple times. The evolution laws of the i th carriage's failure strength σ_f^i and equilibrium length w_{eq}^i are taken as follows:

$$\dot{\sigma}_f^i = \sigma_f^i [-\beta \bar{\alpha}^i + \zeta \cdot \delta(\sigma_f^i - \sigma)], \quad (1)$$

$$\dot{w}_{eq}^i = w_{eq}^i [-\kappa \bar{\alpha}^i - \gamma \cdot \delta(\sigma_f^i - \sigma)], \quad (2)$$

where $\bar{\alpha}^i$ is the degradation rate of that carriage, while the Dirac δ leads to step changes in the strength and equilibrium length when the strength reaches the applied stress. To this end, the constants ζ and γ control the sudden strength increase and equilibrium length decrease caused by pore collapse during quakes, respectively. The constant β controls the rate of reduction of failure strength due to the degradation process, while $\kappa = 1 - \sigma/K$ depends on the elastic stiffness K , so that the actual length of the carriage is then $w^i = \kappa w_{eq}^i$. The overall predicted strain is then calculated from $\epsilon = (H_0 - \sum w^i)/H_0$. Constants β, κ, γ , and ζ are dimensionless, $\bar{\alpha}^i$ and δ carry units of rate, and σ carries units of pressure.

The above model is simple, yet it can explain the creep-quake cycles most generally, and has the ability to accommodate a broad range of porous medium or material degradation processes with minimal changes by adjusting the material parameters and degradation rates appropriately. A key to the emergence of creep-quake cycles lies in the link

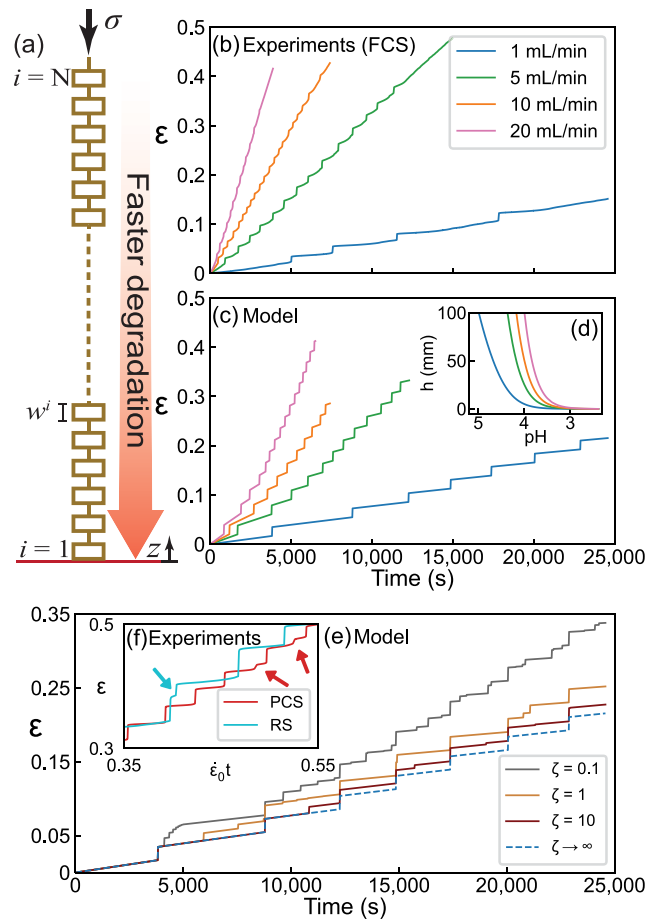


FIG. 4. (a) Elasto-brittle carriages under constant stress σ and degradation field. (b) Strain ϵ over time of fully saturated calcareous sand (FCS) experiments under different acid injection rates. (c) Simulations of each experiment. (d) pH fields recovered from chemical kinetics simulations. (e) The effect of strength recovery post failure through ζ on the irregularity of creep-quake cycles. (f) Similar irregularities observed in other materials (from Fig. 3).

between the degradation of the i th carriage to the local concentration of degrading agent around it, which is captured by the rate of degradation $\bar{\alpha}^i$. In the case of puffed rice, this rate is driven by fluid absorption in particles; for salt and calcareous sand, by dissolution; and in ice, by melting through heat. Considering, for example, the case of calcareous sand saturated in acid, one can recover $\bar{\alpha}^i$ directly from the chemical kinetics of acetic acid and calcium carbonate (see the Supplemental Material) [20], which set the unit of time in the simulations.

In order to evaluate the performance of the model, corresponding experiments with saturated calcareous sand were performed under various acid injection rates, which yielded different strain dynamics, showing quicker material compaction for faster injection rates [Fig. 4(b)]. Through simple numerical integration (details in the Supplemental Material) [20], the model successfully recovers this effect [Fig. 4(c)] thanks to the distinct $\bar{\alpha}$ fields that arise from the pH profile for each flow speed [Fig. 4(d)]. These profiles broadly agree with the experimental observations in Fig. 3(c). Most significantly, the model further recovers the generally consistent regular dynamics of creep-quake cycles observed experimentally. For

sand, this is done by taking $\zeta \rightarrow \infty$, the limit where carriages could only crush once. Conversely, finite values of ζ allow carriages to crush multiple times, thus yielding a more irregular creep-quake dynamics, characterized by a broader range of collapse sizes and recurrence time between events, consistent with some of the other materials [Figs. 4(e) and 4(f)].

Using an array of experiments with different materials, this Letter shows that the creep-quake failure mechanism first discovered in puffed rice can develop in any other porous media, as long as they are subjected to simultaneous nonuniform degradation field and pressure. The ubiquity of this phenomenon was explained using a simple theoretical model that underpinned the development of both regular and irregular collapses, in light of these key factors and the length scale associated with the pore size of the material.

Given the ubiquity of the creep-quake cycle mechanism, we anticipate that the process could be discovered in an even wider range of materials, provided the right experimental conditions. Further studies should allow to pinpoint such conditions, and probe more carefully the sensitivity of the magnitude and frequency of the collapse cycles to the pressure and the nonuniformity of the degrading agent. The model also provides a way to predict conditions that go beyond laboratory constraints. Such a comprehensive understanding

of the creep-quake cycle instability is crucial in order to tackle important problems. For instance, this can support research into the stability of soils exposed to acid rain [29], chemically attacked tailing dams [30,31], CO₂ sequestration sites [32], salt deposits exposed to water filtration [8,33], and icequakes in regions with extreme freeze-thaw cycles [34,35]. None of these problems can be addressed without properly accounting for the instabilities of porous materials under nonuniform material degradation.

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Data Availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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