New experiment to model self-organized critical transport and accumulation of melt and hydrocarbons from their source rocks

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ABSTRACT

A new, simple, and easily reproducible experiment was designed to simulate the production, accumulation, and transport of melt within rock. The transport was found to be of the self-organized critical type. The emergence of self-organized criticality is explained by the availability of hydrofracture propagation as a rapid or ballistic transport mechanism. This mechanism also serves as a mechanism for stepwise accumulation. These findings are confirmed by a numerical model, which shows the emergence of self-organized critical behavior when Darcian transport cannot accommodate transport and the dormant transport mechanism of hydrofracture propagation is activated. Ballistic and self-organized critical transport may play a significant role in the transport and accumulation of geological fluids, such as melt and hydrocarbons. This conclusion has a profound impact on the modeling of many transport processes in geology (e.g., accumulation of melt, oil, and gas).

Keywords: fluids, magma, hydrocarbons, flow, accumulation, self-organized criticality.

INTRODUCTION

The transport of a melt through a rock can be described by the Darcian transport equation of the general form:

$$Q = k \cdot \nabla P + S. \tag{1}$$

Here, ∇P is the gradient driving the transport (hydraulic head), k is a transport coefficient (permeability), S is a source term, and Q is the transport flux. This equation describes diffusive regime transport, because the equation is equal to Fick's law for diffusion. The equation describes a passive situation in which the background matrix is supposed to be essentially unaffected by the flow. It is often assumed that the equation also applies to an active situation, in which the flow modifies the rock structure, as in partially molten rocks (McKenzie, 1984; Brown and Solar, 1998). However, in this case transport is often intimately coupled to a mechanism of accumulation. For example, melt is produced on a scale of cubic micrometers on grain boundaries during progressive melting, and eventually moves up and accumulates to produce cubic kilometer-scale batholiths or volcanic outpourings. The accumulation over >25 orders of magnitude implies a profound modification of the background matrix. Thus, Darcy's equation appears to be insufficient to describe simultaneous flow and accumulation in a source rock, as observed by Stevenson (1989).

ANALOG EXPERIMENTS

Not many experiments investigate, in combination, the processes of production, segregation, and accumulation of melt within rocks (van der Molen and Paterson, 1979; Dell'Angelo and Tullis, 1988; Rushmer, 1995), and usually the samples are too small to develop the full range of structures that are found in partially molten rocks (McLellan, 1988; Brown, 1994). We therefore studied the escape of melt in a simple but novel analog experiment, in which fermentation of a sugar solution produced CO_2 gas. The accumulating and escaping gas was taken as an analog of a segregating melt phase in rocks. Although the CO_2 production grossly exaggerates natural volume changes due to partial melting and no deformation is applied, the system is capable of developing the full accumulation and transport dynamics that may also occur in nature (McLellan, 1988; Clemens and Mawer, 1992; Brown, 1994). The basic setup of the experiment consists of an ordinary glass bottle filled with sand that is immersed in a sugar solution with bakers' yeast (Fig. 1). The gas accumulates in hydrofractures and bubble-shaped voids. The same experiment was also done in a flat (1.5 cm wide) glass tank to enable tracking of individual voids. Occasionally voids would collapse and the gas would open up temporary pathways to drain into other or new voids, or escape out of the sample (Fig. 2). The initial geometry of the voids was dominated by planar hydrofractures. The free upper surface of the sample favored the development of horizontal fractures. After about a day, the geometry evolved to a more bubble-dominated geometry, probably a result of the continuous production and transport of gas that leads to a complete mixing of the system. All the analyses presented in the following refer to the second, steady-state situation.

The escape of gas was recorded by monitoring the liquid level with a floater. The liquid level rose gradually by ~0.03 mm/s, equivalent to a gas production rate of ~0.005% of the sample volume per second, and dropped suddenly when a gas batch escaped the sample (Fig. 3A). Fourier analysis of the floater signal produces a spectrum decaying as $1/f^{\alpha}$, with α

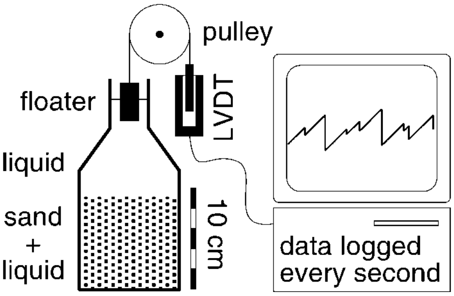

Figure 1. Experimental setup. Wide-necked bottle is filled with sand that is immersed in 250 g sugar + 1 L water solution. Floater is connected to linear variable differential transformer (LVDT), via pulley, to record liquid level by computer every second.

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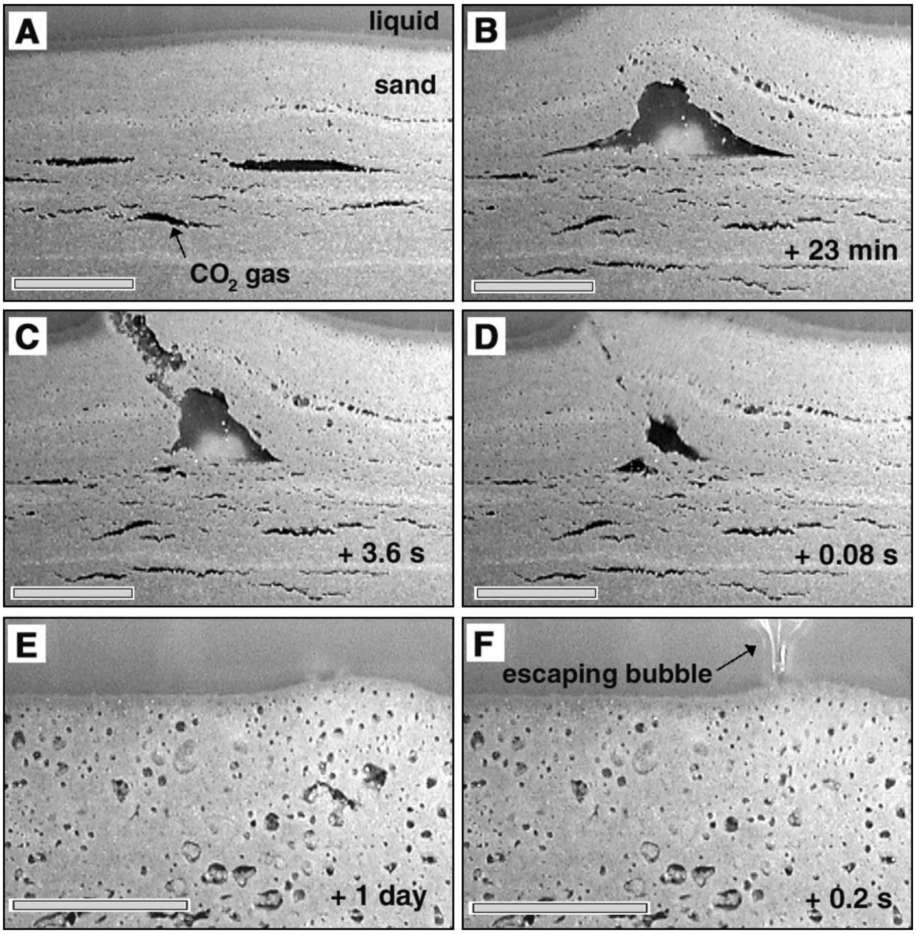

Figure 2. Gas-filled hydrofracture geometry and escape in flat glass tank. A: ~1 h after start of experiment, horizontal hydrofractures are slowly growing. B: One large laccolithic void has formed 23 min later. Large void collapsed 3.6 s later (C) and was drained within 0.08 s (D). After 1 day, gas distribution evolved toward more bubble-shaped voids. E, F: Collapse of such bubbles over 0.2 s interval. All scale bars are 4 cm.

near 1 in the low-frequency (*f*) range and near 2 in the high-frequency range (Fig. 3B). The spectrum is not that of a random signal, which would give a flat power spectrum ($\alpha = 0$). To determine the degree of self-similarity, the rescaled range statistic was evaluated. The rescaled range, *R*/*S*, is the range (*R*) of the variation of the trend-corrected signal, normalized to its standard deviation (*S*) (Mandelbrot and Wallis, 1968). This quantity is plotted versus the time interval (time lag). The logarithmic slope of *R*/*S* versus time lag is known as the Hurst parameter (Hurst, 1951). Uncorrelated, random noise has $H = 0.5$, while a fully correlated signal has $H = 1.0$. For this experiment we find $H \sim 0.9$, indicating significant self-similarity and the existence of strong long-time correlations or memory effects for large values of the time lag (Fig. 3C) (Carreras et al., 1998a, 1998b). The ranked size distribution of the escape events follows a power law, while the distribution of ranked waiting times between escape events is exponential (Fig. 3, D and E) (cf. Boffetta et al., 2000). The sharp decay in the curves of Figure 3D at large volumes is caused by finite-size effects, i.e., the frequency of the largest events is reduced with respect to the power-law expectation due to the limits imposed by the system size (Bak et al., 1988). The largest escaping batch was <10 cm^3 in volume, $\sim1\%$ of the sample. In combination, these results indicate that the experimental system is of the self-organized critical type (Bak et al., 1987; Bak, 1996; Jensen, 1998), and that the self organization of the system occurs for low-frequency events (Fig. 3B) and over long time intervals (to $\sim10^4$–10^5 s) with respect to the auto-correlation time (54 s) (Fig. 3C). The auto-correlation time is the characteristic time over which linear correlations are lost. Nonlinear correlations may still exist over longer time intervals.

Transport events in a self-organized critical system are distributed according to a power law, which implies that rare but large events contribute significantly to the total transport. The largest 5% of escape events account for $\sim$40% of all the escaping gas in our experiments. Furthermore, the largest events propagate at speeds far above the diffusive velocity, i.e., these individual events show ballistic behavior. Due to the presence of such ballistic events, the overall transport will no longer be strictly diffusive and becomes superdiffusive. In the experiment, the average upward flow rate of the gas was about 2×10^{-5} m/s in the 10-cm-high sample column with $\sim$30% gas-filled porosity. Analysis of the collapse of individual voids showed escape flow velocities ≤ 0.5 m/s (Fig. 2C); i.e., more than four orders of magnitude greater.

SELF-ORGANIZED CRITICAL TRANSPORT

Self-organized criticality is a transport mode that typically occurs in strongly driven systems with many degrees of freedom that are far from equilibrium (Bak et al., 1988). These kinds of systems cannot be successfully modeled using equation 1, because the response of the system to an increase of the drive is not to increase the gradient ∇P (as would happen in a system that is governed by equation 1), but rather to open alternative transport channels, using its additional degrees of freedom. In the experiment, the opening of air channels and the associated rapid propagation (analogous to hydrofracture propagation in rocks, Weertman, 1971; Maaløe, 1987; Dahm, 2000) can be regarded as such a flux-activated transport channel. The behavior of such a system with an alternative transport mechanism can be illustrated with a simple cellular automaton (Fig. 4), which was originally designed for heat transport in plasma experiments. The model consists of a row of $N = 100$ cells with pistons, that are pushed up by an incompressible fluid and down by springs (Fig. 4A). Fluid is randomly added in small amounts to each cell. Cells are linked by two transport channels: (1) a diffusive channel through which the flux is proportional to the pressure difference between the pistons and a conductivity parameter (equation 1), and (2) a ballistic channel with a valve that opens when the pressure difference between two pistons exceeds a set threshold (P_{on}) and closes when below a set threshold ($P_{\mathrm{off}} = 0.1 \times P_{\mathrm{on}}$). The pressure between pistons that are linked by open valves is equalized. At the low end of the row of cells, we impose a closed boundary (i.e., it has zero flux), while at the high end, the boundary is open (i.e., it is kept at zero pressure). Transport is purely diffusive (equation 1) at a low filling rate of the pistons, because pressure gradients remain too low to activate ballistic transport. However, when the filling rate is increased, the gradient becomes steeper until a point is reached where valves are opened and rapid (ballistic) transport can take place. The pressure gradient is henceforth controlled by the valve system. Transport is no longer continuous, but characterized by intermittence or bursts with a wide range of am-

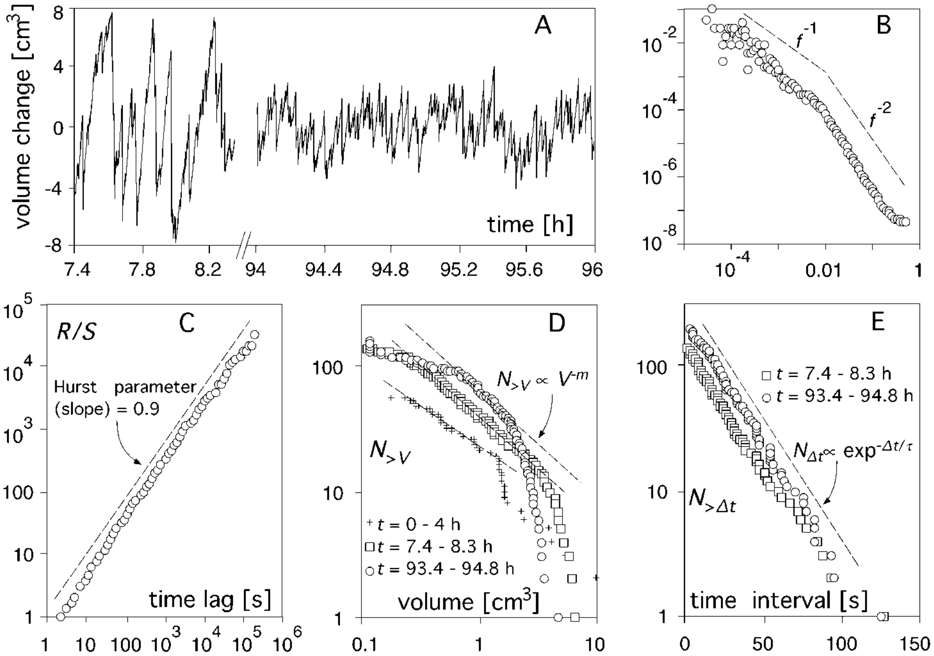

Figure 3. Analysis of floater signal in experiment. A: Time record of sample volume changes (in cm^3) at start and after 4 days, corrected for slow downward trend due to fluid loss (evaporation, consumption of sugar by yeast). Upward slopes indicate expansion of sample due to CO_2 production, while sudden drops correspond to escape of gas from sample. Fluctuations in volume are stronger at beginning of experiment when voids are mostly fracture like. B: Power spectrum of fluid level. C: Self-similarity analysis for 53 h period, starting 93 h after start of experiment, showing rescaled range (*R*/*S*; *R* is range, *S* is standard deviation) vs. time lag. D: Number of escaping batches larger than certain volume ($N_{>V}$) vs. this volume for three time (*t*) intervals. Distribution is power law with exponent *m* ~0.65–0.85. E: Number of waiting times between escape events larger than certain value ($N_{>\Delta t}$) vs. this waiting time (Δt) value for two time intervals. Distribution is exponential with Δt ~22 s.

plitudes. Although it is possible to determine an effective conductivity of the system, this is neither meaningful nor useful; it cannot be used to describe any other flux than the one for which it was determined, because the usual linear relationship between gradient and flux, characteristic of a diffusive system, has broken down (van Milligen and Bons, 2001). In addition, due to finite-size scaling effects (Christensen et al., 1996), such an effective conductivity cannot be applied to systems of a different size. In the new ballistic transport state, the system is best described as a self-organized critical state, and it exhibits fluctuating pressure (Fig. 4B) with a 1/*f* power spectrum (Fig. 4C), a Hurst factor $H = 0.79$ (Fig. 4D), indicating self similarity and long-range correlations, and a probability distribution of the pressure signal that deviates significantly from a Gaussian distribution for the large-amplitude fluctuations (Fig. 4E).

DISCUSSION

The experiment is meaningful as an analog for geological transport processes in rocks if it replicates the same combination of relevant processes. The CO_2 gas can slowly percolate or diffuse through pores and pore fluid, respectively, just as fluids do in rocks. This transport is not efficient enough to dispose of all gas and the gas pressure rises to form gas-filled voids and fractures. Although the detailed fracturing mechanism may be different from that in rocks, the main point is that gas accumulates in voids that are propped open by the internal gas pressure that exceeds the least compressive stress. The same process of hydrofracturing occurs in rocks (Secor, 1965). Hydrofractures in the experiment and in rocks become unstable when they exceed a certain vertical extent and can then propagate rapidly (Weertman, 1971; Spence and Turcotte, 1985; Clemens and Mawer, 1992; Dahm, 2000; Bons, 2001). Brittleness, buildup of fluid or gas pressure, and low fracture strength are the crucial factors that make the experiment a scaled replica of nature. Experiments with purely elastic-brittle gelatin instead of sand and liquid give the same result, which shows that the Mohr-Coulomb behavior of the wet sand is not a critical aspect.

The first indications that the self-organized critical state is actually reached under geological conditions are emerging, especially from numerical models that allow activation of ballistic transport (O'Hara, 1994; Maxwell and Ortoleva, 1997; Phair, 1998; Miller and Nur, 2000). If the self-organized critical state is attained in source rocks of magmas, hydrocarbons, and metamorphic fluids, completely new transport models should be developed that can handle the rich dynamics of such a system, in which batches exhibit differences of many orders of magnitude in volume and transport rates. Fluid-rock or melt-rock interaction would be characterized by periods of stagnation for individual batches, variable chemical equilibration, bursts of rapid transport, and step-wise mixing of batches (Maaløe, 1987; Richardson et al., 1996). The transport model we propose is reminiscent of the fault-valve model of Sibson et al. (1988), which envisages a cyclical increase in fluid pressure until hydrofracturing is induced and excess fluid is rapidly drained from the system. The same happens in our model, but over a range of scales in a self-similar manner. Sibson et al. (1988) suggested a regular cyclical fluid flux, which would produce a sharp peak in the power spectrum of the flux as a function of time. Instead, our model of self-organized critical transport indicates that the flux would not have such a regular cyclicity, but 1/*f* behavior (Figs. 3B and 4C).

Sobolev et al. (2000) suggested that small magma batches are able to ascend through the mantle without interacting with their surroundings. This could be related to the rapid ballistic transport envisaged here. Another possible field example of ballistic transport is the pulsed discharge of oil bubbles in the Gulf of Mexico (MacDonald et al., 2000), where slow seepage of oil from a seafloor spring is punctuated by occasional release of large volumes of oil that rapidly ascend from >2 km depth. This case illustrates the importance of recognizing ballistic transport modes and self-organized critical states: occasional measurement of outflow from the spring would only recognize the slow, diffusional regime seepage and would underestimate the total discharge (MacDonald et al., 2000). In a self-organized critical system, transport is strongly concentrated in few events, which may easily be overlooked due to the usually limited exposure in the geological record. The far more abundant evidence of small events may only tell us a small part of the story and may even be misleading.

CONCLUSIONS

Much current work on fluid transport is based on diffusive regime models, which cannot correctly describe a self-organized critical system, and tend to underestimate the transport capacity of these systems. Our experiments and numerical modeling indicate that a partial melt system may quickly evolve to a self-organized critical state. Melt would gradually accumulate in growing batches that can be transported rapidly and in sudden bursts in propagating hydrofractures. A critical advantage of this model over others is that transport and accumulation are intimately linked. Similar conclusions apply

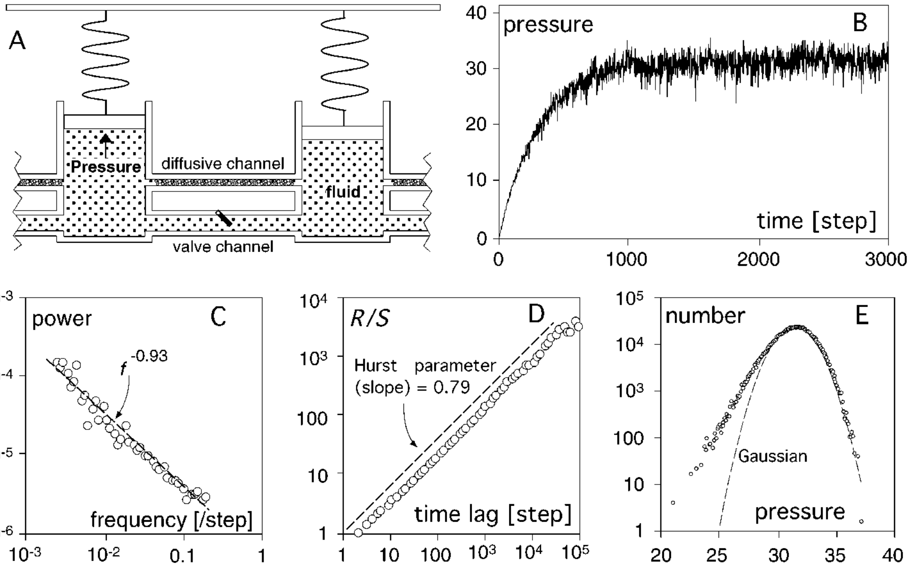

Figure 4. Transport characteristics of combined diffusive and ballistic (self-organized critical) transport in cellular automaton. A: Model consists of linear array of fluid-filled pistons that are pushed down by springs. Incompressible fluid is added in small random amounts to each piston. Pistons are linked by two transport channels: one for diffusive regime transport (transport proportional to pressure gradient) and one for ballistic transport, represented by channel with valve (valve opens when pressure gradient exceeds threshold, leading to pressure equalization between connected pistons). *P* is pressure. B: Pressure as function of time for first 3000 time steps. After ~1000 time steps, dynamic steady-state situation is reached. C: Power spectrum of pressure, showing 1/*f* behavior characteristic of self-organized critical systems. D: Self-similarity analysis of pressure, yielding Hurst parameter of *H* = 0.79, which is indicative of existence of long-range correlations (memory effects). Rescaled range (*R*/*S*) is plotted vs. time lag. E: Probability distribution function of pressure fluctuations in steady state (cf. B), showing distinct deviation from Gaussian distribution for large-amplitude excursions. All curves are for pressure of piston number 50, halfway through model of 100 pistons.

to the transport and accumulation of oil, gas, and metamorphic fluids.

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