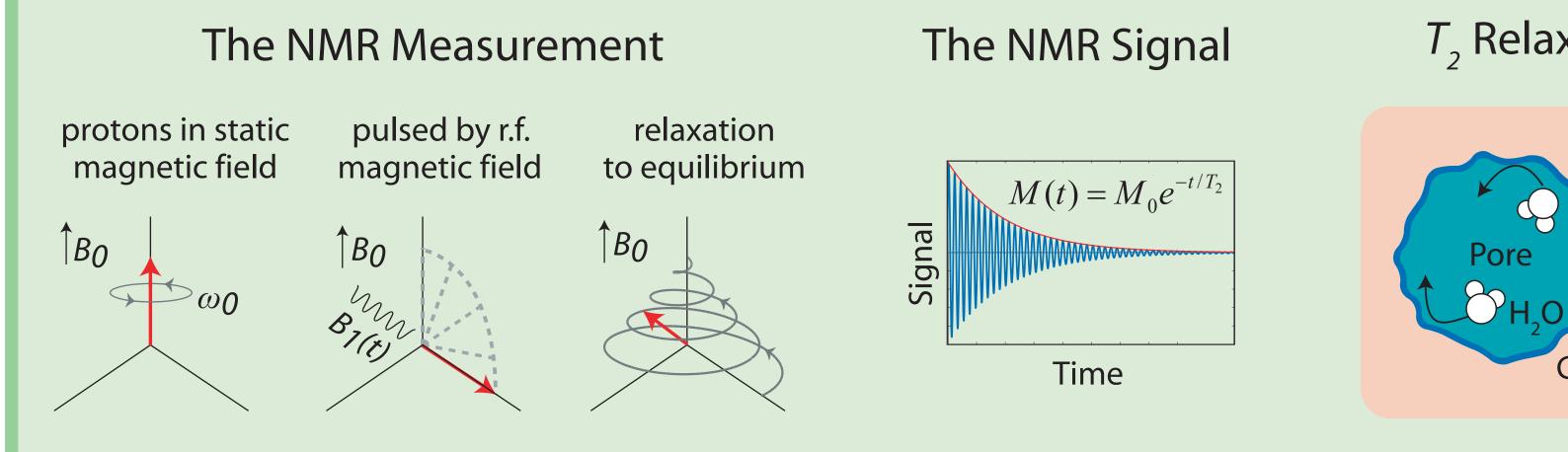


Estimating Pore-Scale Properties from NMR Relaxation Time Measurements in Heterogeneous Media Elliot Grunewald and Rosemary Knight, Department of Geophysics, Stanford University elliotg@stanford.edu, rknight@stanford.edu

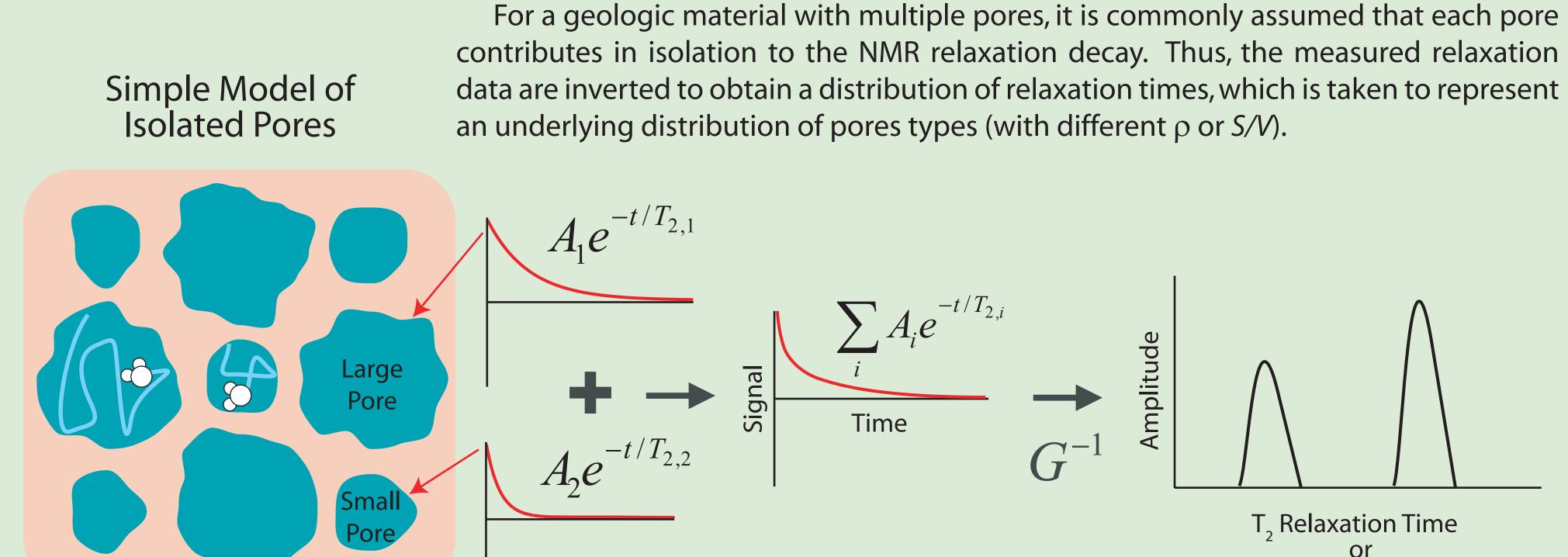
1) Motivation: Estimating Pore-Scale Properties

Proton nuclear magnetic resonance (NMR) relaxation measurements are utilized in geophysical applications to estimate pore-scale properties key to predicting the flow of water and transport of contaminants in the subsurface. The NMR method probes the time required for hydrogen nuclei in water to relax to equilibrium through diffusion and interactions with the pore environment. Conventional interpretation of NMR relaxation data utilizes a model of isolated pores in which each proton samples only one pore, and the distribution of relaxation times is taken to represent an underlying distribution of pore environments. However, this simple model commonly breaks down for heterogeneous materials in which diffusing protons sample multiple pore types before relaxing, introducing socalled "pore coupling" effects. In this laboratory study, we explore the NMR response of heterogeneous porous media and directly investigate the effects of pore coupling on the interpretation of NMR measurements.

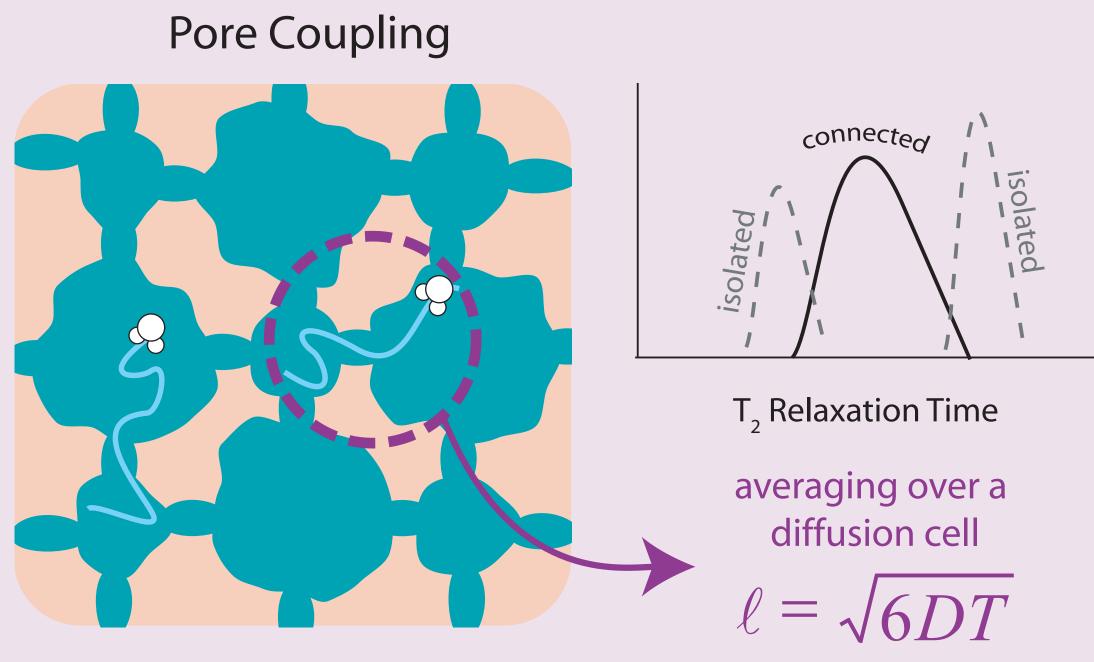
2) Background: NMR Relaxation Theory



In a single pore, the relaxation time T_2 reflects the rate at which protons relax to equilibrium through interactions with the pore-scale environment. This rate depends primarily on the surface-area-to-volume ratio S/V of the pore (i.e. pore size) and the surface relaxivity ρ of the grain surface (concentration of paramagnetic species).



3) Problem: What Happens When Protons Sample Multiple Pore Environments?



The isolated pore model requires that each proton sample only one pore type during the NMR experiment. Yet during relaxation, a water molecule will diffuse over a finite volume defined by the diffusion length. For materials with wellconnected pores, a proton may thus sample multiple pore environments before relaxing. When this pore coupling process dominates, the relaxation-time distribution will reflect a complex averaging of the pore network that can be difficult to interpret. Our research explores the conditions in which pore coupling occurs and its effect on NMR measurements in heterogeneous media.

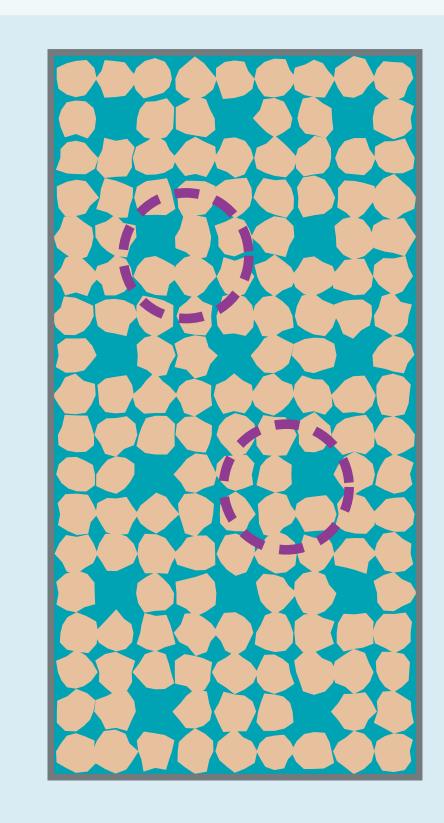
T, Relaxation in a Single Pore

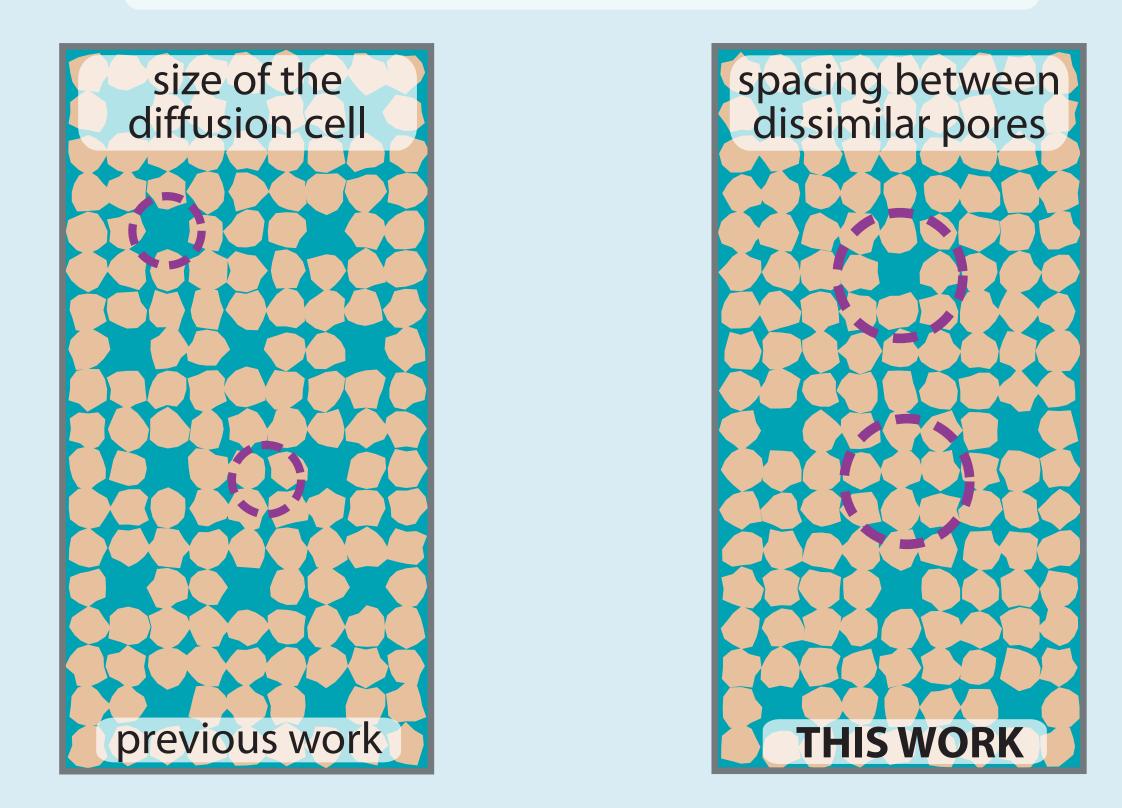
 $\frac{1}{T} = \frac{1}{T} + \rho \frac{S}{V}$ $-2 I_{2B}$ T_{2B} bulk fluid T_{2} surface relaxivity surface-area-to-volume ratio

Relative Pore Size

3) Experiments: Extent and Effect of Pore Coupling

pore coupling significant



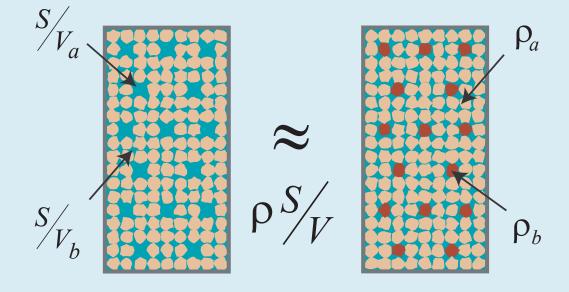


Theoretically, the extent to which pore coupling will occur depends on two critical length scales: the diffusion length and the spacing between dissimilar pores. When the diffusion length is greater than the spacing length, pore coupling will dominate because the majority of protons sample multiple pore environments before relaxing. On the other hand, when the diffusion length is the shortest scale, most protons sample only one pore type, and coupling effects will be limited. Thus, factors affecting either of these length scales must be carefully considered when interpreting NMR data.

A previous laboratory study by Grunewald and Knight [2007] analyzed systems in which the degree of coupling varied as a function of the diffusion length. When paramagnetic Fe (III) was sorbed to the surfaces of silica gels, the average surface relaxation time decreased, hence limiting the distance over which protons could diffuse before relaxing. In this complementary study, we explore systems in which the spacing between dissimilar pore types is directly varied and evaluate the extent and effect of pore coupling for this range of samples.

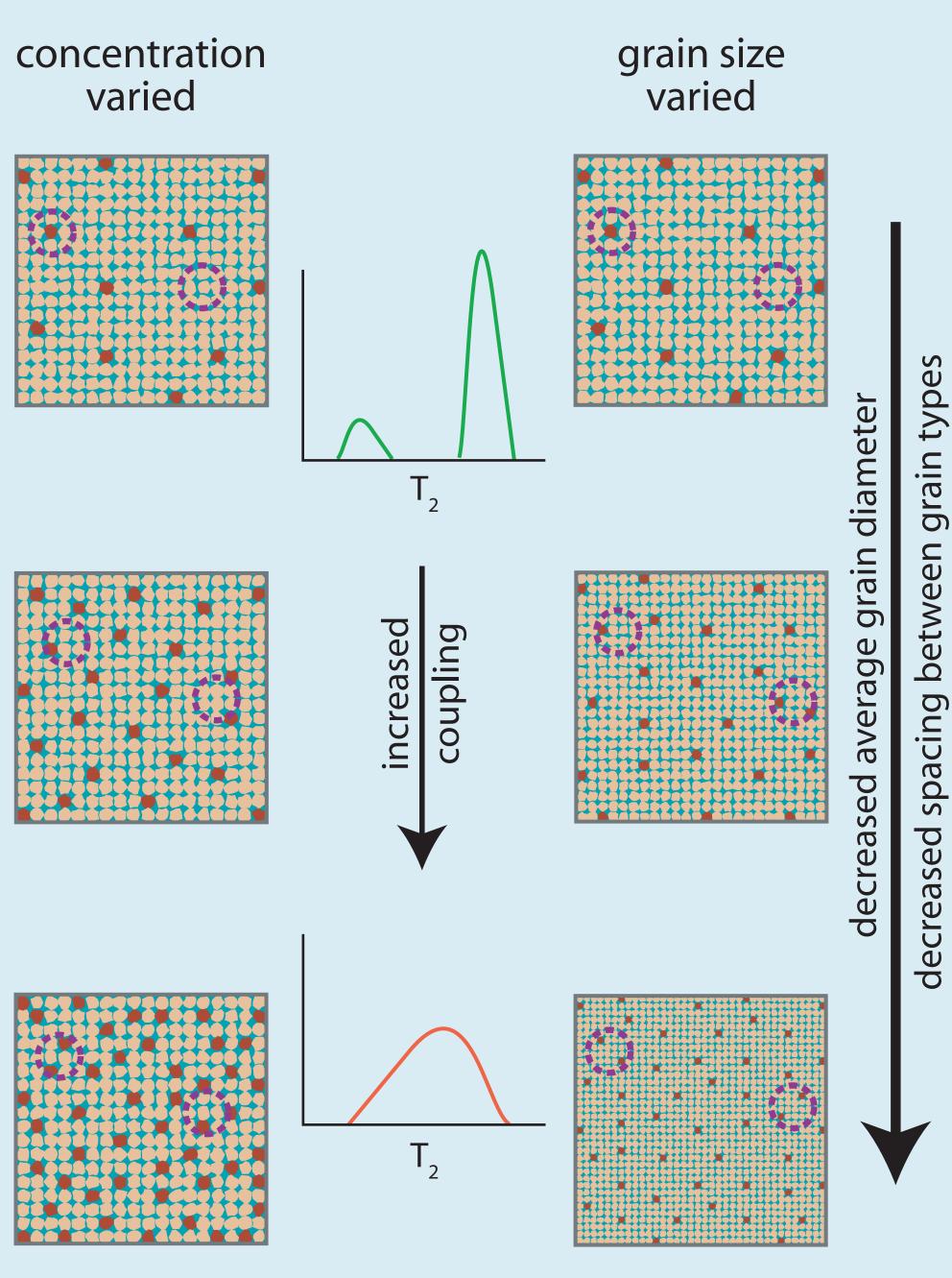
Experimental Design

As it is difficult to control the geometry of samples with a bimodal pore size, we instead study systems with a bimodal mineralogy (i.e., bimodal ρ). Such materials are frequently found in nature and should generally exhibit an analogous NMR response.



Samples were created by mixing low-p quartz and high-p hematite sands at varied concentrations. We anticipated that as the concentration of hematite increased, the spacing between hematite grains would be reduced and pore coupling effects would develop. We further hypothesized that reducing the average grain size would decrease this spacing distance and thus result in enhanced coupling. Therefore, samples were also mixed for two different grain sizes: coarse-grained $(d\sim 200 \ \mu\text{m})$ and fine-grained $(d\sim 45 \ \mu\text{m})$.

pore coupling effects limited by varying ...





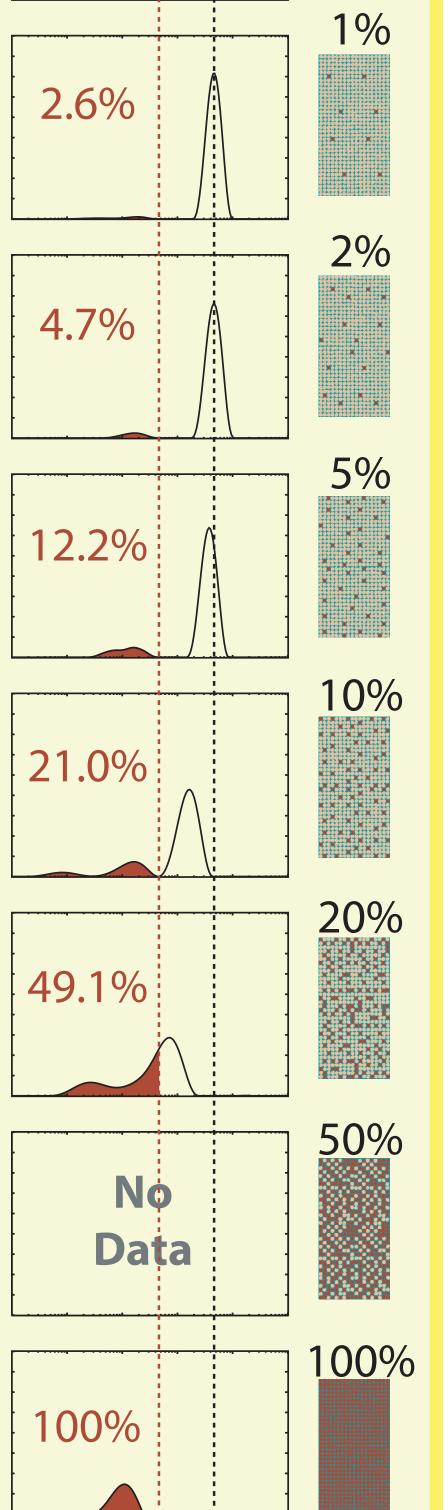
We are currently conducting numerical simulations of NMR relaxation in analogous systems in order to extend and generalize results from our laboratory measurements. Using random-walk simulations we are able to efficiently model relaxation in heterogeneous systems and directly investigate the evolution of relaxation in both time and space. By combining laboratory and numerical results, we hope to develop a widely applicable model of relaxation in unconsolidated heterogeneous media to improve the interpretation of NMR data in near-surface applications.

References and Acknowledgments

Grunewald, E. and R. Knight (2007) A laboratory study of NMR relaxation times and pore coupling in heterogeneous porous media, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract NS31B-0378.

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For the fine-grained samples, we note similar results with the



 $^{-4}$ 10⁻³ 10⁻² 10⁻¹ 10⁰

fine-grained

 $d = 37-52 \,\mu m$

0.5%