# Convergent flow observed in a laboratory-scale unsaturated fracture system[1]

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Received 1 July 2002; revised 29 August 2002; accepted 16 September 2002; published 29 January 2003.

[1] An experiment was designed to observe water flow in a simple analogue fractured rock network. The fracture network was modeled by the gaps between an array of limestone blocks, whose permutations generated different realizations of the network. Three out of five of these realizations displayed flow convergence, in contrast to that predicted by porous continuum models. Such convergence occurs because fracture intersections act as capillary barriers that integrate or focus flow within the network. *INDEX TERMS:* 1875 Hydrology: Unsaturated zone; 5104 Physical Properties of Rocks: Fracture and flow; 5139 Physical Properties of Rocks: Transport properties; 5194 Physical Properties of Rocks: Instruments and techniques. **Citation:** LaViolette, R. A., R. J. Glass, T. R. Wood, T. R. McJunkin, K. S. Noah, R. K. Podgorney, R. C. Starr, and D. L. Stoner, Convergent flow observed in a laboratory-scale unsaturated fracture system, *Geophys. Res. Lett.*, *30*(2), 1083, doi:10.1029/2002GL015775, 2003.

## 1. Introduction

[2] It was recognized in the last decade that flow in unsaturated fractured media with a low-permeability matrix might not be always diffusive, i.e., continuously spreading in the directions orthogonal to the direction of infiltration. Instead, it was proposed, via a thought experiment, that the flow might focus or converge even in the absence of strong heterogeneity, ultimately flowing down only a few fractures in an otherwise pervasively fractured rock formation [*Glass et al.*, 1995]. Diffusive behavior is expected from the traditional volume-averaged porous continuum model of flow physics, wherein any irregularities within the flow field would be attributed to heterogeneities in the material properties. Figure 1 illustrates these two circumstances. For the diffusive case, the flow creates saturation profiles that spread throughout the medium. For the convergent case, discrete flow paths combine with depth.

[3] The presence of focused or convergent flow within unsaturated rock formations has been suggested in the literature, e.g., [*Russell et al.*, 1987]. A variety of evidence shows rapid and deep penetration of meteoric water in fractured vadose zones, e.g., [*Fabryka-Martin et al.*, 1996; *Davidson et al.*, 1998], as well as in field-scale [*Glass et al.*, 2002a] and other laboratory-scale infiltration experiments [*Glass et al.*, 2002b]. Nevertheless, the direct observation of convergent flow has been elusive. The thought experiment proposed by *Glass et al.* [1995], led us to conduct the following experiments where flow in a fractured unsaturated media could be observed.

## 2. Experiment

[4] The experimental system employed twelve limestone blocks nominally 30 cm × 7 cm × 5 cm to form a vertical plane 90 cm high and 28 cm wide, with three rows of four blocks. (The blocks of Northern Grey Buff Minnesota Stone dolomitic limestone were obtained from Vetter Stone Co., Kasota MN, USA. We measured their porosity (12%–15%) and permeability (1–10 md).) The gaps between the blocks play the role of fractures. The blocks were held together with a horizontal compressive load. The entire system was encased in transparent plastic, which reduced evaporation. Irregularities in the block surfaces due to saw cuts employed in fabrication led to variable aperatures within the fracture network. Where four blocks came together, an intersection was formed with additional irregularities dues to imperfections along the corners of the blocks. Tapwater chemically equilibrated with the blocks was supplied from loadcells at the top of the network, at equal rates (1 ml/min) to each of the three fractures. Fiberglass wicks 30 cm long were connected to the bottom of the vertical fractures; therefore the suction applied to the bottom was equivalent to a hanging column the height of one block. Loadcells were employed for both the supply and recovery bottles for each fracture to verify the inflow rate. Figure 2 sketches the apparatus and the geometry of the blocks.

[5] Five configurations were constructed in which the blocks for each were randomly permuted within the geometry specified above, i.e., three rows of four blocks in a vertical plane (Figure 2). Experiments were conducted on each of the configurations, each initially dry. The infiltration process was recorded with time-lapse video; by 24 hours, all blocks in all arrangements were wet. A sequence of frames (spanning over nine hours) in one of the

[1]Supported by the INEEL Environmental Systems Research and Analysis Program, Office of Environmental Management, U. S. Department of Energy.
[2]Operated for the U. S. Department of Energy under DOE-ID Operations Office Contract DE-AC07-99ID13727.
[3]Operated for the U. S. Department of Energy under DOE-AL Operations Office Contract DE-AC04-94AL85000.


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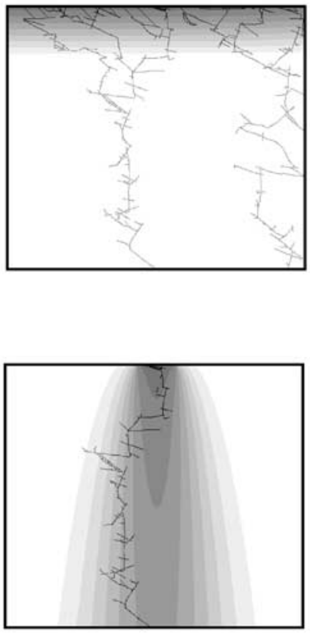

**Figure 1.** The panels each sketch the difference between diffusive flow (in shaded gray) and convergent flow (lines). The top panel corresponds to infiltration by water from many sources distributed along the surface; the bottom panel corresponds to a single source localized on the surface.

arrangements with converging flow is shown in Figure 3. One sees a stop-and-go dynamic as the water moves through the network to breakthrough (less than 2 hours). Water moves rapidly down to an intersection and then waits. At least one horizontal fracture at an intersection is spanned and then after a further wait, water continues downward but now often as a combined flow from two fractures above. After breakthrough (greater than 2 hours), the blocks continue to wet from the water flowing within the fractures, and, occasionally, additional fractures begin to carry some flow.

[6] Of the 5 permuted configurations tested, 3 displayed convergence at the scale of the experiment. One of the three arrangements that displayed converging flow was tested three more times, without rearrangement, with different degrees of initial wetness. All four of those tests displayed similar converging flow.

[7] Even with only five independent samples (corresponding to the five permutations of the blocks), a quantitative estimate of the uncertainty in the mean occurrence of converging flow can be achieved via the bootstrap method [*Efron and Tibshirani*, 1993]. The bootstrap with exact enumeration gives $\frac{3\pm1}{5}$ for the mean occurrence of converging flow at the 80% confidence level. Therefore, the occurrence of converging flow is at least as statistically significant as the occurrence of uniform flow in these experiments.

## 3. Discussion and Conclusion

[8] The cause of convergent, or focused, flow has been attributed to pathway integration by capillary barriers. Multiple pathways from above are combined in the pool above a capillary barrier. When this barrier breaches, it tends to do so at a single location from which the integrated flow emanates. In our experiment, the intersections of the horizontal and vertical fractures between blocks act as capillary barriers. Nevertheless, subsequent to breaching the intersection, the water was observed to enter one of the two horizontal fractures, fill it, and then breach the lower vertical fracture and continue downward. This breaching process has been observed in another context by [*Wood et al.*, 2002]. It is this added behavior of the horizontal fractures during the intersection invasion process that results in convergence. Where two vertical fractures are connected by a filled horizontal fracture, the combined flow tends to enters the vertical fracture that breaches first, leaving the other vertical fracture empty. (An additional focusing can occur if a horizontal fracture is already filled when water reaches the intersection from above. From the geometrical arguments employed elsewhere for pores [*Glass and Yarrington*, 1996], the pressure to breach the barrier will be lowered in this case, thus facilitating the spanning of the intersection to the horizontal fracture that was initially filled, and causing the capture of a lagging pathway by a leader.) The sequential application of this process causes continued pathway convergence. Of course, for convergence to continue with depth, the pathways must come into contact via capillary barriers of increasing scale, but this requirement is likely to be fulfilled for a wide variety of fractured systems.

[9] In conclusion, the results of this study support the conjecture of *Glass et al.* [1995]. Converging flow was observed in a laboratory-scale fracture network, apparently for the first time. The mechanism for local convergence within the fracture network is due to the combined behavior of fractures and fracture intersections as flow conduits and distributed capillary barriers, respectively.

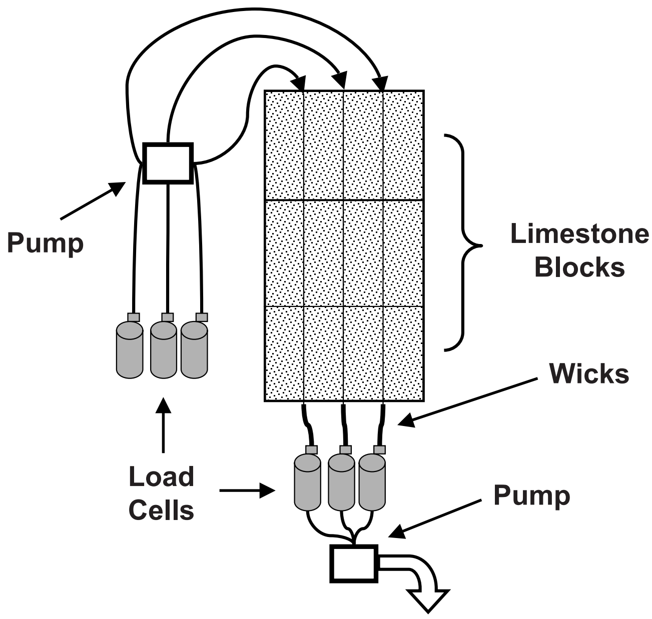


**Figure 2.** Schematic of the experimental apparatus.

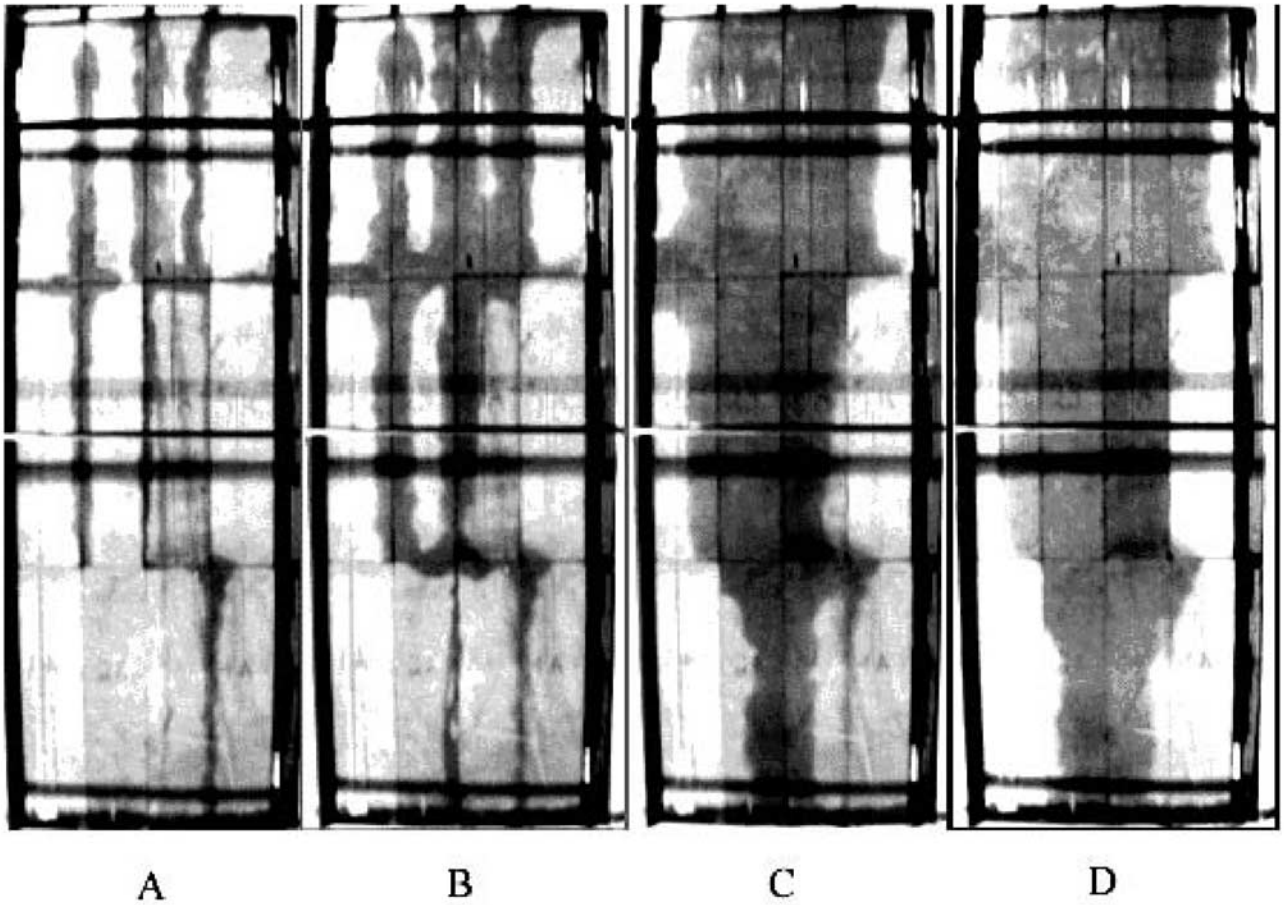


**Figure 3.** Photographs of water infiltrating an arrangement of 12 blocks, at the following times (in minutes): (a) 50.3, (b) 107, (c) 219, and (d) 609. The thick horizontal lines are the clamps and their shadows.

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