PATTERN FORMATION

Watch your step

Beautiful, intricate patterns in limestone result from feedback between hydrodynamics and chemistry. This self-organizing process resides in an unfamiliar region of parameter space for systems of deposition under fluid flow.

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In most rivers and streams, rapid flow is associated with erosion, calmer flow with deposition. This is the reason why the river channel stays fairly localized, although it can also move laterally. Many of the most striking landforms on Earth — for example the Grand Canyon, the tree-like branching of the rivers of the Amazon basin and the meandering patterns that form on river plains — are due to this relationship. But what if it were the other way around? What would happen if deposition were faster in regions of rapid flow? The travertine terracing system described by John Veysey and Nigel Goldenfeld on the *Nature Physics* website today[1] provides a prime example, and the resulting patterns are simply astonishing.

Travertine is a form of limestone (basically calcium carbonate) precipitated from water flowing over a surface. It forms around hot springs, such as in Yellowstone National Park, in streams originating in mountainous limestone areas, and in limestone caves. Travertine often grows into bizarre shapes, including stalactites, stalagmites and domes. It can also form spectacular patterns of cascading dams known as travertine terraces or rimstone. These landscapes of steps on small and large scales evoke a feeling of surreal, unearthly mystery, no doubt due to the uncommon relationship between flow rate and deposition.

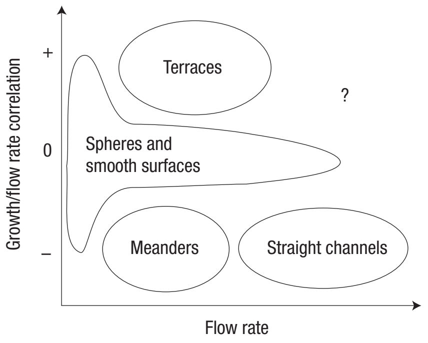

Figure 1 Sketch of the parameter space for surface growth and erosion/dissolution under fluid flow. The upper region, where growth is faster in areas of rapid flow, is unfamiliar and little explored.

Veysey and Goldenfeld use a simple, elegant computational approach to the fluid flow problem, coupled to a water-chemistry model. The precipitation rate depends on flow rate, with terms covering flow normal to the surface and effects due to degassing of carbon dioxide. In such modelling, there is always a trade-off between generality and ease of interpretation on the one hand, and attention to the details of the interactions on the other. Veysey and Goldenfeld take a middle position, including a number of processes but on a somewhat abstracted level (in 2007, my colleagues and I took the abstraction even further, reducing the system to simple proportionality between flow rate and precipitation[2]). In any case, the details of many of these interactions are not yet precisely known. The simulated patterns and their development in time are compared with careful time-lapse studies of a natural system, demonstrating that the model is sufficiently detailed to reproduce statistical properties of the dams.

These statistical properties are in themselves of interest. Using simulations, careful measurements of the natural system and also theoretical arguments, Veysey and Goldenfeld show that above a small-scale cut-off the landscape is scale-invariant with respect to pond area. They further find good correspondence between terrace width distributions and a theoretical null-model, implying that the interactions between terraces are mainly short-ranged.

The physicist should make no apologies for investing energy into problems of specific application to a particular process in nature. Science is about more than finding general laws that can be immediately put to use in other scientific disciplines or in technology. Science is also about observing beautiful, intriguing natural processes, and having the curiosity to want to find out how they work. The general public, and especially children, understand and appreciate this almost aesthetical aspect of science very well, funding bodies sometimes less so.

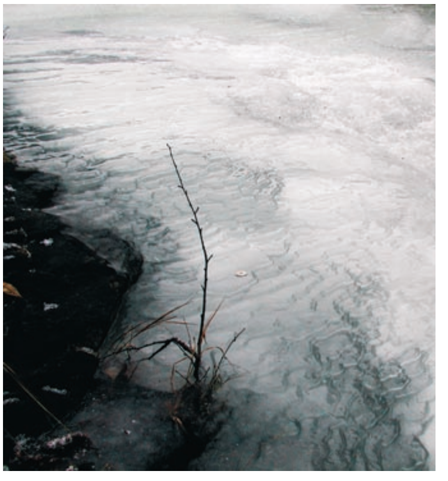

Figure 2 Ice terraces forming under a thin sheet of flowing water demonstrate an unusual pattern formation regime. Note coin for scale.

The paper by Veysey and Goldenstein is a good example of visually appealing science that is intuitively understandable in spite of its fairly advanced methodology, but the basic process the authors demonstrate does indeed have wider implications. On a theoretical level, it provides an example of a fluid flow/surface growth system in a rarely explored region of parameter space for such pattern formation processes. Figure 1 shows such a parameter space. Whereas the lower region of this space is well known to us in the form of river erosion and deposition, the upper region is largely *terra incognita* where more work is needed. The travertine system could be useful in this respect because it can occupy any region of the parameter space depending on the degree of saturation of calcium carbonate: undersaturated water will dissolve limestone (which is how a limestone cave is formed) depending on flow rate[3].

On a more applied level, limestone precipitation under flow is a process of great industrial significance; being responsible for scaling in pipes and boilers it creates considerable financial losses. Moreover, travertine terracing is far from the only example of this class of system. We see almost identical patterns in systems where precipitation is connected with heat flux away from a flowing sheet of water, such as terraces of water ice on sloping surfaces (Fig. 2) and silica terraces around hot springs. In other situations, the association between flow rate and surface growth may be due to consolidation of the surface under ballistic deposition, such as in the so-called litter dams forming from leaves and pine needles on forest paths after a heavy rainfall.

So next time you go to a hot spring, limestone cave, a forest, or anywhere icy, watch out for those steps. Not only are they strange and beautiful — they represent a phenomenon of general significance, and after reading the article of Veysey and Goldenfeld you will also know something about how they form.

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References

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3. Buhmann, D. & Dreybrodt, W. *Chem. Geol.* **48**, 189–211 (1985).