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Travertine terracing: patterns and mechanisms

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Abstract: Travertine terracing is one of the most eye-catching phenomena in limestone caves and around hydrothermal springs, but remains fairly poorly understood. The interactions between water chemistry, precipitation kinetics, topography, hydrodynamics, carbon dioxide degassing, biology, erosion and sedimentation constitute a complex, dynamic pattern formation process. The processes can be described and modeled at a range of abstraction levels. At the detailed level concerning the physical and chemical mechanisms responsible for precipitation localization at rims, a single explanation is probably insufficient. Instead, a multitude of effects are likely to contribute, of varying importance depending on scale, flux and other parameters.

Travertine terracing is undoubtedly among the most spectacular geological phenomena on Earth. Ranging in vertical scale from millimetres to tens of metres, travertine terraces form intricate, delicate patterns as well as imposing waterfalls. Such terraces are common not only in limestone caves and around hot springs, but also in streams and rivers in limestone terrain (Pentecost 2005, 59–66). In addition, analogous patterns are found in completely different systems, such as silica sinter deposits and water ice. Some of the more spectacular examples of travertine terracing are found in Yellowstone National Park (Bargar 1978; Fouke *et al.* 2000), Pamukkale in Turkey (Altunel & Hancock 1993), Huanglong Scenic District in China (Lu *et al.* 2000) and northern Spitsbergen, Norway (Hammer *et al.* 2005). A list of travertine occurrences in Europe and Asia Minor with notes on terracing was given by Pentecost (1995). Travertine terraces formed an inspiration for Renaissance ornamental water cascades (Berger 1974). However, in spite of their great interest, both aesthetically and scientifically, the formation of travertine terraces has until recently received only scattered scientific attention, especially on the theoretical side (Wooding 1991 provides one notable exception).

When trying to understand this pattern formation system, a series of fundamental questions arise. What processes are responsible for the enhanced precipitation at the terrace rim? On a higher level of abstraction, how do these local processes lead to global self-organization? How do the terraces evolve in time, and what are their statistical properties under different conditions? Answering such questions requires a cross-disciplinary approach, involving field work, laboratory experiments, computer modeling and mathematical theory in order to study the complicated feedbacks between hydrodynamics, water chemistry, calcium carbonate precipitation and possibly particle transport and biology.

Morphology and hydrodynamics

The terminology of travertine terrace morphology is confusing. Speleologists often use the roughly equivalent terms 'rimstone' and 'gours', with 'microgours' referring to cm-scale terraces. For open-air travertine systems, morphological classification schemes have been proposed by several authors. Pentecost & Viles (1994) define 'barrages' as terraces that are filled with water, forming pools and lakes. 'Cascades' are smoother forms on steep slopes, often with smaller terrace-like structures superimposed on them (Fig. 1). Pentecost (2005) uses 'dams' instead of barrages. Fouke *et al.* (2000) and Bargar (1978) use three size categories of barrages, namely 'terraces' with areas of tens of square metres, 'terracettes' of a few square metres and 'microterracettes' of a few square centimetres or less (Fig. 2). Microterracettes are therefore analogous to microgours. Pentecost (2005) suggests the term 'minidam' for a dam with an interdam distance (IDD) ranging from 1 cm to 1 m.

In this paper we will use the classification of Fouke *et al.* (2000), extending it to the analogous speleothems. In addition, we recognize that on steep slopes, microterracettes will not form pools (and are therefore not barrages) but grade into subdued 'microridges' normal to flow. We also use 'terrace' as a general term regardless of size. We use 'rim' for the top of the outer wall of the terrace, and 'pool' for the water body behind it. The rim is usually convex outwards (downstream), or consists of a series of near-parabolic lobes pointing in the downstream direction (Fig. 2). Inside pools, flow velocity is small due to the larger

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Fig. 1. Travertine terracettes (left) and cascades (right). Mammoth Hot Springs, Yellowstone National Park, USA.

Fig. 2. Terraces, terracettes and microterracettes at Mammoth Hot Springs, Yellowstone National Park, USA.

depth, and the travertine morphologies are often botryoidal or 'stromatolitic' with porous textures, reflecting a diffusion-dominated regime often with substantial biological activity. These 'shrubs' are often assumed to have a bacterial origin (e.g. Chafetz & Folk 1984) but can probably form from purely inorganic processes (Jettestuen *et al.* 2006). Over the rim and on the steep outside wall of the terrace, water flows in a thin sheet and flow velocity increases. Here, the travertine is usually more compact.

A basic observation is that travertine terraces seem to display scaling properties, with microterracettes often having similar morphologies as the largest terraces. As a working hypothesis we might postulate that a similar mechanism is responsible for pattern formation at all scales, and that a continuous coarsening process could lead from smaller to larger terraces. However, at the smallest scales surface tension exerts an important influence on the hydrodynamics, producing 'bags' of water overhanging the rim and a meniscus at the base of the exposed drop wall (Fig. 3). In most localities it can be observed that the height of terracettes and microterracettes is fairly constant, on the order of 4–5 mm, regardless of slope, thus producing pools of much larger area in regions of small slope (Fig. 4). In fact, given a constant height h and a minimum inter-dam distance k, we can geometrically predict the IDD as a function of slope angle α:

$$\mathrm{IDD} = \frac{h}{\tan\,\alpha} + k$$

Data given by Pentecost (2005) seem to fit this simple model well (Fig. 5). Conversely, if the underlying slope is constant, the IDD will also be nearly constant. This effect may contribute to the possible characteristic wavelength which will be discussed below. The 'unit-step phenomenon' can be explained by the fact that the surface-tension meniscus lapping onto the rear wall of the pool can only reach to a certain constant height, allowing free flow from the upstream rim over the wetted terrace wall. Given the temperature control on surface tension, terracette height might possibly vary with temperature. At larger scales, surface

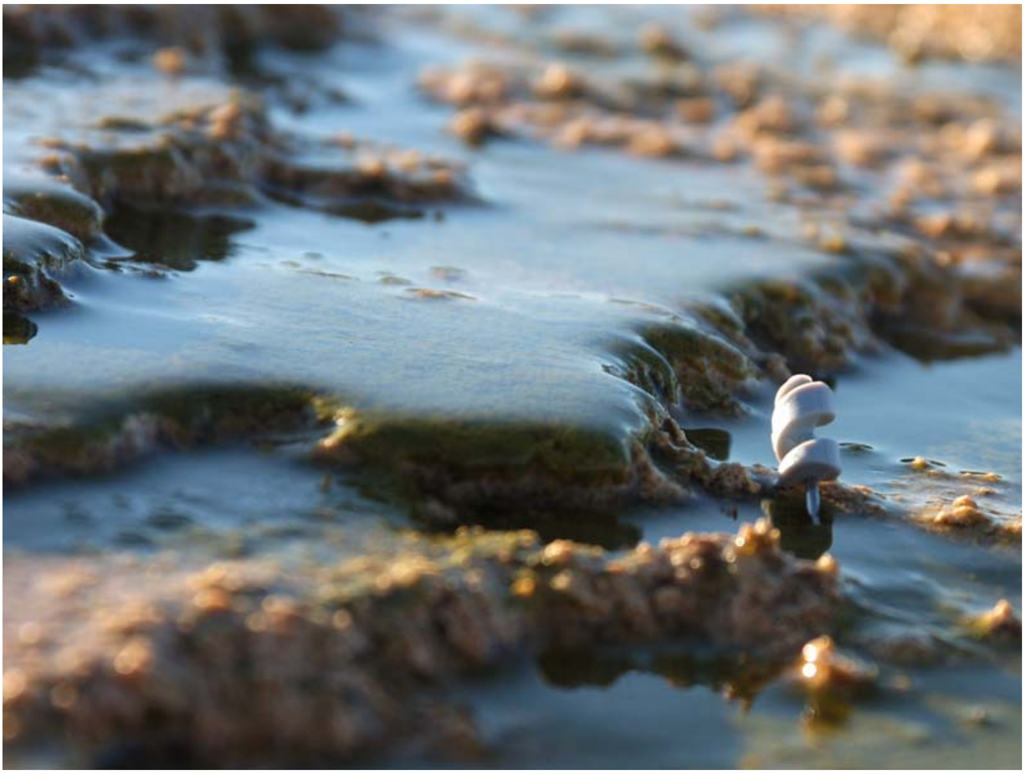

Fig. 3. Due to surface tension, 'bags' of water hang over the rims of these microterracettes at the Jotun hydrothermal spring, northern Spitsbergen. Message board peg for scale.

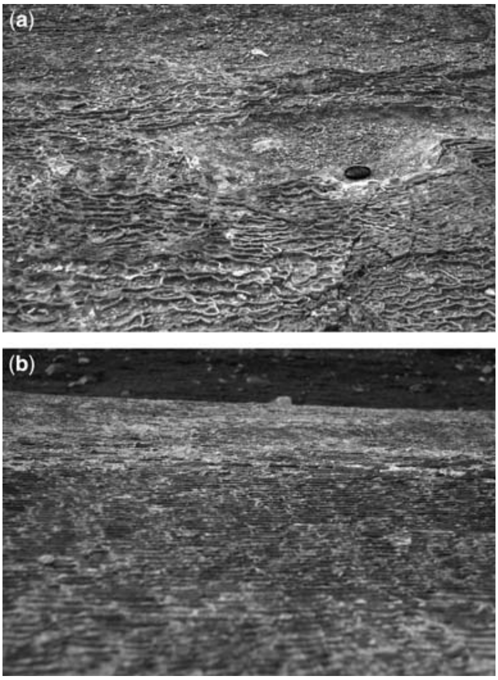

Fig. 4. Dried-up microterracettes at the Troll hydrothermal springs, Spitsbergen. Lens cap for scale. The almost constant height of terracettes implies larger pool areas in regions of small slope. (a) Oblique view. (b) Horizontal view from the same position.

tension loses importance and unit steps are not observed.

Travertine terraces owe some of their beauty to the almost perfectly horizontal orientation of the rims. Any artificially added protuberance will reduce water flow and precipitation locally, allowing the surrounding rim to catch up, while any incised notch will increase flow locally but divert flow away from the rest of the rim, causing relatively faster precipitation in the notch. Clearly, a flat rim will have a tendency to 'self-repair', restoring to a stable horizontal line after perturbation. In fact, water flow over the rim is rarely uniform, but localized to a number of narrow sites (Fig. 6). Clearly, these sites are continuously repositioned, producing a statistically uniform growth rate along the rim over time.

Terrace dynamics

The emergence and dynamics of travertine terraces can be studied with a number of techniques. Cross sections of travertines allow direct observation of relative growth rates and depositional sequences. The travertine quarries of Rapolano Terme in Italy offer spectacular exposures (Guo & Riding 1998; Hammer *et al.* 2007), demonstrating general increase in scale and steepness with time (upwards coarsening), higher precipitation rates at rims and terrace walls, and upstream or usually downstream migration (Fig. 7).

Several authors have mapped travertine precipitation rates in natural terraced systems (Liu *et al.* 1995; Lu *et al.* 2000; Bono *et al.* 2001; Hammer *et al.* 2005). These studies demonstrate substantially higher precipitation rates in areas of high flow velocity near terrace rims and walls, causing relative upwards and outwards growth of the rims.

The most spectacular method for the study of travertine terrace dynamics is time lapse photography. Veysey & Goldenfeld (2008) produced a movie based on a year-long data series from the Mammoth Hot Spring complex in Yellowstone National Park, showing progressive coarsening by pond inundation where the rim of a pool grows faster than the rim of the upstream pool, causing drowning of the upstream pool and the formation of a single large pool. Their movie also shows downstream migration of terraces.

The formation and expansion of downstream-pointing lobes is seen both in time lapse movies and in simulations. Hammer *et al.* (2007) attempted to explain this 'fingering instability' by observing that the regional, underlying terrain slope implies a higher and steeper terrace wall at the downslope tip of the lobe than at the sides. As discussed below, this leads to faster precipitation rates at the tip of the lobe and therefore differential downslope migration rates of the rim, causing a downslope stretching of the pool.

It is commonly observed that terrace systems are partly dry (Fig. 6a). This is not always due primarily to reduction in overall flux. As a result of travertine build-up, water continuously finds new routes. Old pathways may be abandoned and dry up, but become active again at a later date (Chafetz & Folk 1984).

Pattern formation mechanisms

Travertine terracing is a self-organizing pattern formation process involving a number of coupled physical processes. Several authors have recently modeled the process at different levels of abstraction, highlighting different aspects of the problem.

At the purely geometric level, it is clear that a simple relationship between slope steepness and growth rate is sufficient to produce a terraced pattern. Starting from a rough slope with small random perturbations, Jettestuen *et al.* (2006) used such a growth rule to computer simulate the emergence and coarsening of steps. Interestingly, the

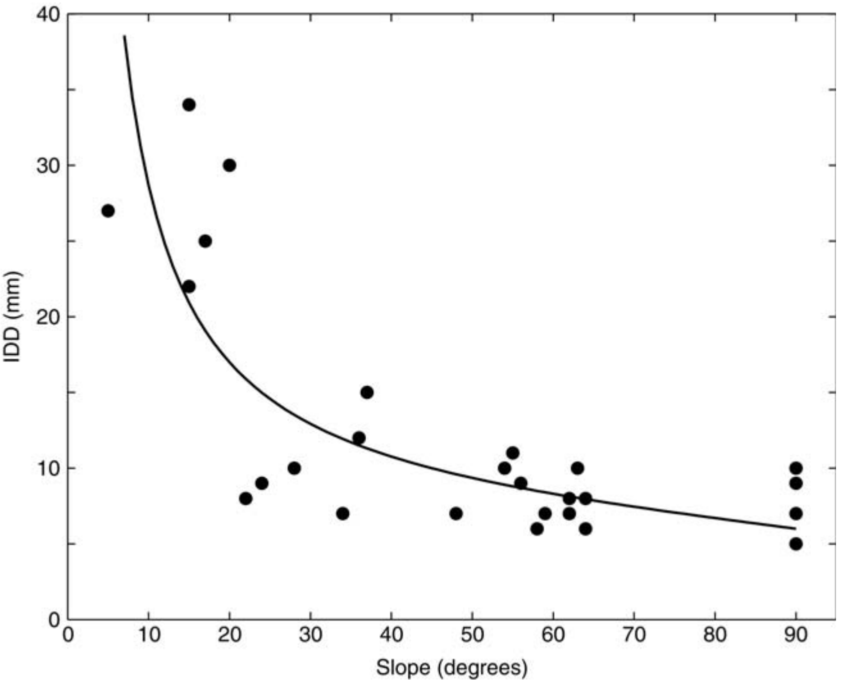

Fig. 5. Dots, Slopes and inter-dam distances (IDD) measured in minidams by Pentecost (2005). Line, Theoretical IDD with constant terrace height $h = 4$ mm, minimal IDD $k = 6$ mm (see text).

resulting morphology was reminiscent of the scalloped microterracettes seen on steep travertine surfaces with thin film flow, where flow velocity is fairly well predicted by slope alone. For a film thickness h, gravity g, slope α, kinematic viscosity ν and an empirical constant K, we have

$$\bar{u} = \frac{8gh^2 \sin\alpha}{K\nu}$$

(Horton *et al.* 1934). However, in order to understand the mechanism for the slope-precipitation relationship, a more detailed model is required. Hammer *et al.* (2007) used a computer simulation of shallow water flow over a surface (computational fluid dynamics), coupled with a simple precipitation model where growth rate was proportional to flow velocity. This produced a proximal mound and distal apron covered with terracettes, coarsening

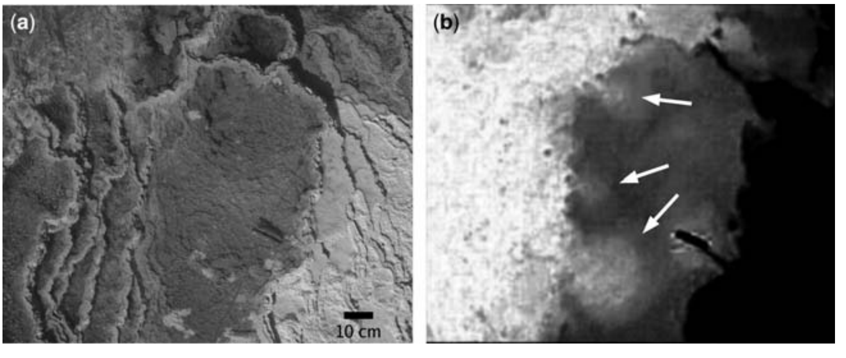

Fig. 6. Visible-light (**a**) and infrared (**b**) images of the same area in Mammoth Hot Springs, Yellowstone National Park, USA. Hot water flow from left to right. Lower right area (bright, Fig. 6a) is dry. Plumes of hot water (arrows, Fig. 6b) in the largest pool demonstrate localized flow over the upstream rim.

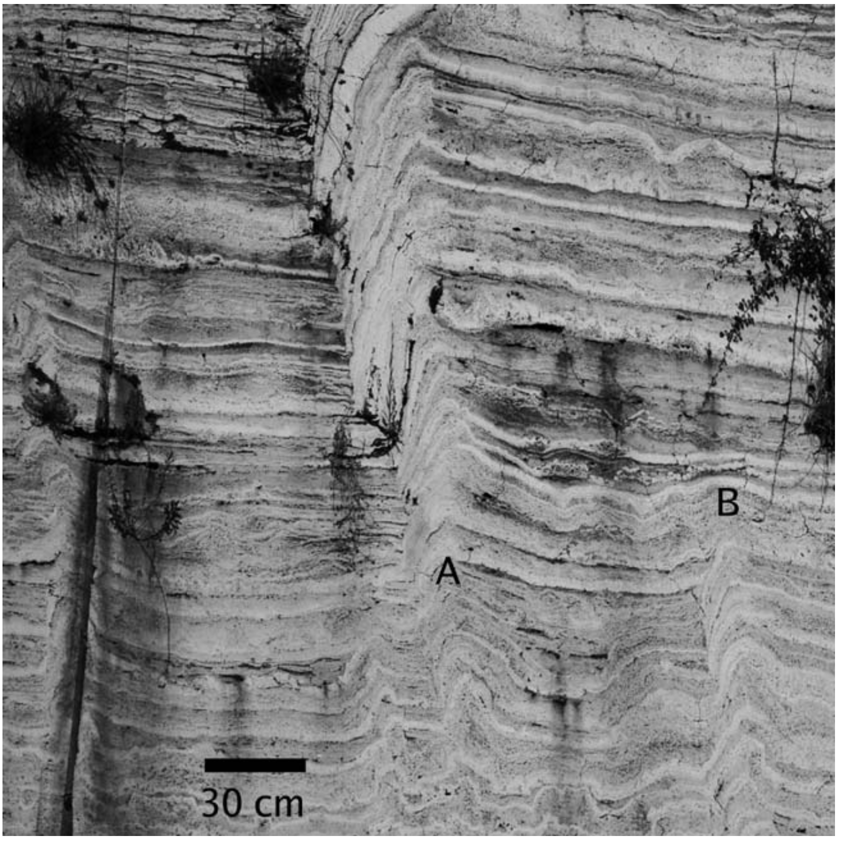

Fig. 7. Cross section of travertine at Rapolano Terme, Italy. Flow was from right to left. Note the initiation and upwards coarsening of rim A, leading to the upstream drowning and termination of rim B.

with time. Rims folded into lobes and migrated downstream with differential rates. In such a model, high flow rates are found not only on steep slopes, but also in shallow regions over rims where velocity must increase to maintain the flux. This provides a positive feedback mechanism between hydrodynamics and precipitation on the rim, leading to localization of precipitation and the stabilization and growth of rims.

Goldenfeld *et al.* (2006) and Veysey & Goldenfeld (2008) developed a much more detailed cellular model, including simplified rules for water flow, surface tension, water chemistry and outgassing of CO_2. Their precipitation rule included idealized terms incorporating oversaturation level, flux normal to the surface, and flow velocity. The simulated travertine terraces were natural-looking and reproduced statistical properties observed in the field (see below). Considering the work of Hammer *et al.* (2007) it is likely that the flow rate term in the precipitation rule is the most important cause of terrace formation in the simulations of Veysey & Goldenfeld (2008).

Mechanisms for precipitation localization

The models described above assumed a relationship between flow rate and precipitation, but did not address in detail the mechanism for such a relationship. In addition, it is conceivable that the relationship is not causal, but that both quantities reflect other, underlying causes. An extraordinary variety of mechanisms have been proposed to explain the higher precipitation rates at terrace rims.

A popular explanation has been increased outgassing of CO_2 at rims due to agitation and shallowing, the latter increasing the local surface to volume ratio (Varnedoe 1965; Chen *et al.* 2004). Considering the travertine system as a whole, under normal (e.g. not hyperalkaline) conditions calcite precipitation depends on loss of CO_2 from aqueous solution to the atmosphere (e.g. Dreybrodt *et al.* 1992). An extremely simplified, cartoon-like equation, summarizing many partial reactions that are variously important at different pH, can be written as

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CO_2 + CaCO_3 + H_2O$$

In the classical model for calcite precipitation and dissolution in karst settings by Buhmann & Dreybrodt (1985), it is therefore assumed that precipitation/dissolution rate is stoichiometrically equal to outgassing/ingassing. However, this holds true only under equilibrium conditions and at large scales. In the presence of non-homogeneous advection and diffusion, local, small-scale variations in outgassing at the water-atmosphere interface are not echoed by corresponding local variations in precipitation rate at the bottom, at least in deep water relative to flow rate (Hammer *et al.* 2008).

One promising application of the outgassing hypothesis is the case of thin, laminar film flow, forming microterracettes on steep surfaces and ridges on stalactites. Ogawa & Furukawa (2002) studied the problem of ridge formation on icicles, which are analogous to stalactites but with precipitation being dependent on heat loss rather than CO_2 loss. They explained the characteristic ridge wavelength as a result of two competing processes. Thermal diffusion in air involves steeper temperature gradients and therefore faster heat transport around protrusions, encouraging the formation of structure at small wavelengths (so-called Laplace instability). However, thermal transport in the flowing water film makes the temperature distribution more uniform, suppressing small wavelengths. Ueno (2003) carried out a similar analysis, but emphasized the role of gravitational and surface tension forces on the water film to explain the suppression of short wavelengths.

Several authors have invoked the Bernoulli effect as a mechanism for increased outgassing under rapid flow, leading to faster precipitation (Chen *et al.* 2004; Veysey & Goldenfeld 2008). This effect refers to the lower fluid pressure associated with higher flow velocities. Hammer *et al.* (2008) showed that even at a very high flow rate of 1 m/s, this effect would lead to only about 0.5% pressure drop at the water-air interface. The corresponding 0.5% decrease in dissolved gas concentration under equilibrium conditions, according to Henry's law, is unlikely to have a major effect on precipitation rates.

Mixing in the water column will strongly increase precipitation rates by efficiently bringing solutes to and from the calcite surface. In the case of turbulent flow, we can assume almost complete mixing in the turbulent core away from the travertine surface. Precipitation rates will then be limited by diffusion of solutes through the laminar boundary layer. Since the thickness of the boundary layer decreases with flow rate, this provides a mechanism for a causal link between flow rate and precipitation rate (Buhmann & Dreybrodt 1985). This idea has been confirmed experimentally (Liu & Dreybrodt 1997; Dreybrodt *et al.* 1997) and by comparison with field measurements (Dreybrodt *et al.* 1992; Liu *et al.* 1995). Wooding (1991) presents a particularly interesting analysis of the growth of individual travertine and ice terraces, using a similar conceptual model. However, this model primarily applies to turbulent flow, and can not explain pattern formation at the smallest scales under shallow, slow laminar flow.

Hammer *et al.* (2008) developed a detailed, mechanistic model of carbonate precipitation on an imposed obstruction in shallow 2D laminar flow, with the aim of understanding the localization of precipitation on terrace rims (Fig. 8). This model included hydrodynamics, diffusion of solutes, solute carbonate chemistry, precipitation kinetics and outgassing, and compared well with laboratory experiments. A Laplace instability (Ogawa & Furukawa 2002) caused enhanced precipitation in regions of high convex curvature. In addition, precipitation was high in the shallow, high-velocity region on top of the obstruction, but also in a position downstream from the obstruction. Dramatic experimental increase of outgassing in local positions in the model had no effect on precipitation patterns. Hammer *et al.* (2008) concluded that advection is of central importance, by bringing ions to and away from the calcite surface. This was also implied in the model of Goldenfeld *et al.* (2006), which includes a term in the precipitation model for flow rate normal to the surface. In addition, solute concentration gradients set up in a pool are geometrically compressed when advected through the shallow region over the rim. This results in steeper gradients and therefore faster vertical diffusion, leading to enhanced precipitation. Additional possible mechanisms include ballistic deposition of carbonate particles onto the rim from suspension (cf. Eddy *et al.* 1999) and biological effects (Chafetz & Folk 1984).

Statistical properties

The quantitative morphology (morphometrics) and size distribution of travertine terraces as a function of parametres such as slope, flux and water chemistry have not yet been studied in detail. It is possible that shape or size descriptors could be useful proxies for the reconstruction of, for example, paleoflux. However, statistical properties of terraces in individual settings have recently been subject to investigation.

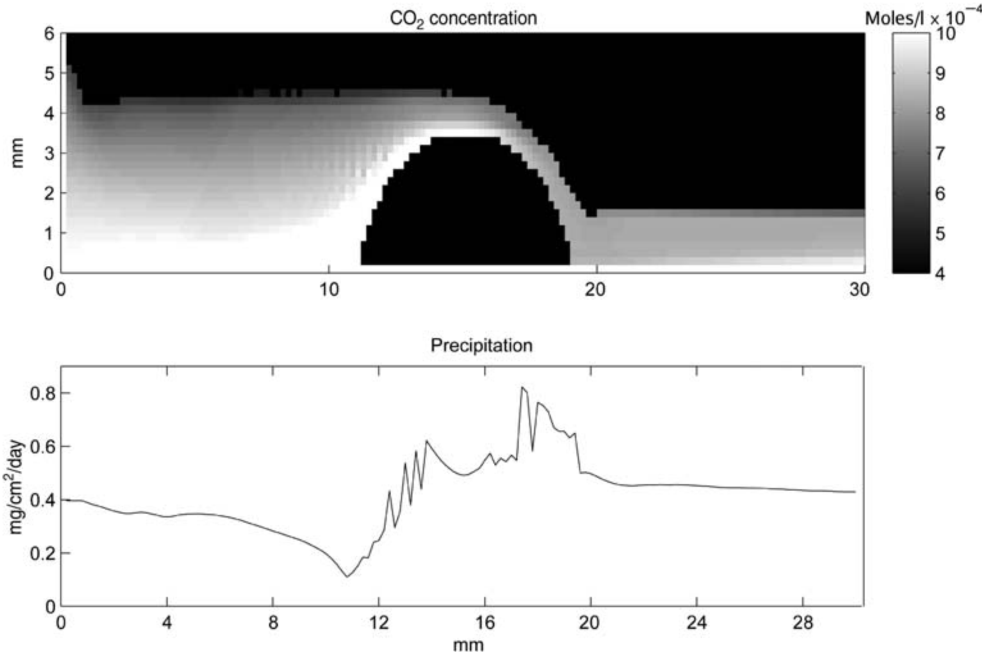

Fig. 8. Computer simulation of calcite precipitation under shallow water flow over a protuberance (flow from left to right). Top: Map of CO_2 concentration. The upstream concentration gradient is compressed over the obstruction. Downstream there is thorough mixing until a gradient slowly reappears at the far right as CO_2 is released by precipitation. Bottom: Precipitation rate, showing enhanced precipitation on the top of the obstruction and also downstream. Small peaks are due to the computational grid, causing small corners of the obstruction to stick out from the boundary layer. The model includes hydrodynamics, advection, diffusion, degassing, solute carbonate chemistry and precipitation kinetics. Details of simulation in a somewhat different geometry are given by Hammer *et al.* (2008).

Pentecost (2005) discusses terrace wavelength in the downstream direction and the relationships between slope, discharge, terrace wavelength, depth and height. In general, pools are shorter on steep slopes, but height can be larger. Inter-dam distance (IDD) seems to increase with larger discharge. The IDD sometimes displays a characteristic wavelength. In the study by Viles & Pentecost (1999) IDD was found to be random, but in this case terraces were possibly initiated by large woody debris. For microterracettes, the ratio between IDD and depth is higher on gentler slopes.

Hammer *et al.* (2007) studied terracette topography in downstream cross sections, both using their simulation results and field observations in Rapolano Terme, Italy. In spite of the problems of such cross sections cutting the pools at random transversal positions, and not always at their widest points, a regular spacing (characteristic wavelength) was observed.

Microterracette pool width distributions were studied in great detail by Veysey & Goldenfeld (2008), again using both simulation and field data. They defined their pool width as the largest width in a direction normal to the maximum chord. Comparing with a statistical null model of Brownian-motion (random walk) rim shape, they found good accordance except for small terrace widths. Although their distribution is unimodal, it has large variance, and is somewhat difficult to reconcile with the more regular spacing observed at larger scales by Hammer *et al.* (2007). Veysey & Goldenfeld (2008) interpreted their results as indicating no interaction between rims for large terrace widths, but an attraction effect for small widths.

Veysey & Goldenfeld (2008) also present an interesting analysis of pool areas. Using a simple null model of initially small-sized pools merging randomly, they show that the expected steady-state pool area distribution is inverse-square, in accordance with their field observations.

General aspects of travertine terrace pattern formation

Pattern formation in the travertine terrace system results from the interaction between two opposing

Fig. 9. Microterracettes in Pamukkale, Turkey, seemingly displaying a characteristic spacing.

processes: enhanced growth at the rim constituting local positive feedback, and long-range negative feedback involving both reduced growth in the pools and upstream inundation. In a very general sense, travertine terrace patterning can therefore be included in the local self-activation/lateral inhibition class of pattern formation systems (Gierer & Meinhardt 1972, 2000). Such systems typically produce patterns of regularly spaced points, or parallel or labyrinthic stripes, as observed in many biological and geological settings. In the travertine terrace system, the lateral inhibition proceeds predominantly upstream, by the pool dammed by the rim. The possible regular spacing between rims in the downslope direction (Fig. 9, and Hammer *et al.* 2007; but see Viles & Pentecost 1999 and Veysey & Goldenfeld 2008) may be understood in terms of this theoretical framework. However, the mechanism for lateral inhibition involves advection driven by complex hydrodynamics rather than simple isotropic diffusion, producing intricate morphologies.

High travertine precipitation rates are generally found in positions of high flow velocity, whether or not there is a causal relationship between the two. In this respect, the travertine terrace system is precisely the opposite of more familiar systems of erosional flow (Hammer 2008). In high-velocity locations in rivers and streams the substrate is typically removed, rather than accreted, leading to localization of the flow channel. In contrast, water flow in the travertine terrace system is generally diverging, and the pools sprawl out laterally in mutual competition. This unusual pattern formation regime may be responsible for the surreal impression invoked by travertine terrace landscapes.

Conclusions

There is probably not a single mechanism responsible for localization of precipitation at the rim in all circumstances. At small scales with slow, laminar shallow water flow, we suggest that the Laplace instability effects suggested for ice by Ogawa & Furugawa (2002) and Ueno (2003) and confirmed in a travertine terrace setting by Hammer *et al.* (2008) can initiate microterracing. When the ridge begins to affect bathymetry and hydrodynamics, advective effects come into play by dampening small-wavelength features (Ogawa & Furugawa 2002; Ueno 2003), by bringing ions to and from the calcite surface (Veysey & Goldenfeld 2008; Hammer *et al.* 2008) and by compression of concentration gradients over the rim (Hammer *et al.* 2008). At slightly larger scales and for faster flow, turbulence sets in and diffusion-limited precipitation becomes dependent on flow rate by thinning of the laminar boundary layer (Buhmann & Dreybrodt 1985). At even larger scales relative to water depth and flow rate, spatial patterns of outgassing across the water-air interface can reach the water–calcite interface and open up a positive feedback loop involving loss of CO_2. Across all scales and flow rates, mechanical sticking of particles on the rim may also play a role. Surface tension affects the hydrodynamics especially at smaller scales, influencing terrace morphology.

In spite of recent results, travertine terracing remains an intriguing problem. Although there are many candidate mechanisms, the precise nature of precipitation localization under different conditions is not known. Do terrace size and spacing stabilize under certain conditions, or do they always continuously coarsen? When do we see terrace size distribution following a random null model (Veysey & Goldenfeld 2008) and when do we see a characteristic wavelength (Ogawa & Furukawa 2002)? What effects do parameters such as flux, oversaturation and slope have on patterning, and why? Such questions can probably be answered through a combination of computer simulations, theoretical studies, field studies and laboratory experiments, but the complexity and diversity of the system should not be underestimated. As noted by Veysey & Goldenfeld (2008), travertine precipitation is a convenient geological process to study because of the relatively fast processes. In addition, the accessibility of this earth-surface system, the availability of analytical and computational techniques, the cross-disciplinary nature of the problem and the sheer beauty and mystique of travertine terraces all make travertine terracing an attractive area of research.

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