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Experimental landform development by rainfall erosion with uplift at various rates

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ABSTRACT

Four runs (1, 2, 3, and 4) of physical analog model experiments, in which a square (ca. 60 × 60 cm) column of a mixture of fine sand and kaolinite is slowly raised at different rates (ca. 5.1, 1.3, 0.5, 0.2 mm/h, respectively) under artificial rainfall of about 38 mm/h, were conducted to observe how experimental landforms develop in relation to these uplift rates. As a square mound gradually emerges from ground level, fluvial erosion starts at the mound edges and develops into valley systems. This process of fluvial erosion, expressed in a linear relationship between *relief* (maximum height–minimum height) and *mean cell slope* (mean value of the highest slope gradient in a 1 cm × 1 cm grid cell), dominates until *relief* reaches about 60 mm, around the time when slope failures (slumps) start to dominate. If fluvial erosion dominates throughout the run (*relief* stays below 60 mm), the uplift rate is considered to be below the lower threshold and landform development is in the "characteristic relief phase." In all four runs, *relief* increases above 60 mm and slumps become significant as hills grow, indicating that uplift rates in this series are above the lower threshold. In run 1, the uplift at a high rate overwhelmed erosion and a massive mountain-like topography formed despite the occurrence of large slumps. The uplift rate in run 1 is thus above the upper threshold and landform development is in the "mountain building phase." The mountain is likely to collapse when it grows higher than the limit of mountain growth determined by factors other than uplift rates. In runs 2, 3, and 4, after valley systems develop over the surface, hills grow with the occurrence of slumps and channel profiles seem to become stable at gradients corresponding to the uplift rates. As slopes grow steeper than a certain "critical gradient," which is possibly the angle of repose of dry mound-forming material, they become vulnerable to slumps. However, slopes of material containing water and clay can grow steeper than this gradient in the absence of triggering events. The frequency distribution of *cell slopes* becomes bimodal, indicating the dominance of two types of slopes divided by the critical gradient, one below and another above. The former represents surfaces formed mainly by fluvial processes, and the latter surfaces formed by and/or waiting for slumps. Slumps reduce *relief*, but average height (*zmean*) does not fall unless sediments produced by slumps are carried away by fluvial processes. The combination of slope failure, fluvial processes, and uplift eventually works to keep *zmean* stable around a certain height depending on uplift rates, while *relief* repeats decrease and increase. The experimental landforms in runs 2, 3, and 4 seem to have achieved a certain steady state with uplift and erosion. The landform development in these runs is considered to be in the "steady-state phase," with uplift rates between the lower and upper thresholds. These observations and interpretations are surprisingly consistent with studies on real landforms and can be of value in interpreting their development.

1. Introduction

The observation and interpretation of processes operating during the development of experimental landforms subject to rainfall erosion and uplift have potential value for studying mountain range formation and the evolution of landforms in general (e.g., Schumm et al., 1987; Paola et al., 2009). Such experiments allow detailed observations in a time sequence of landform development at the experimental scale, whereas the long-term development of real landforms usually has to be estimated from fragmentary evidence in the geologic record or extrapolated from short period measurements. The development of real landforms should of course be explained from the evidence of the landforms themselves rather than from models. However, physical analog model experiments can still have an important role in providing ideas for interpreting scarce and fragmentary evidence obtained from real landforms.

A series of physical analog model experiments in which small erosion landforms develop from the interaction between rainfall erosion and uplift at different rates led me to propose the existence of two threshold uplift rates, across which experimental landforms show

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different modes of development (Ouchi, 2011). When the uplift rate is below the lower threshold, erosion is almost exclusively fluvial and a certain characteristic relief reflecting the erodibility and rainfall intensity appears. When the uplift rate is above this lower threshold, areas dividing drainage basins grow into hills or ridges, and slope failure becomes significant. Erosion by a combination of slope failure and fluvial processes soon roughly balance the rise of the land surface in response to uplift, if the uplift rate is below the upper threshold. Above the upper threshold, uplift overwhelms erosion and high mountains possibly grow until uplift stops or until the mountains meet a growth limit.

This paper reports a new series of rainfall-erosion experiments with uplift at various rates and discusses the effects of uplift rate on the long-term development of experimental erosion landforms, especially whether the thresholds exist and how experimental landforms develop in relation to the uplift rates.

2. Experimental procedure and results

2.1. Facilities and procedure

The facilities used in the previous series of experiments (Ouchi, 2011) were improved for the new series. The uplift area was reduced to 600 × 600 mm (and the width of the deposition area surrounding the uplift area to 600 mm), and a new uplift-generating device, which has a stepping motor and worm gears, was installed (Fig. 1). The material (a mixture of fine sand and kaolinite, 10:1 by weight) and rainfall (very fine rain from tape-shaped tubes for irrigation) were fundamentally the same as for the previous series. The material was compacted in a square prism-shaped stainless container (ca. 600 × 600 × 350 mm) and pushed up a little at a time periodically (every 20 or 30 min) from ground level by the uplift-generating device set beneath the bottom plate (Fig. 1). In contrast with the previous series, in which rainfall erosion was initiated on a square mound about 120 mm high, each run in the new series began with a flat surface at ground level. The average permeability of the material was $3.4–4.6 \times 10^{-4}$ cm/s, and artificial rainfall (ca. 38 mm/h) was applied on and around the area of uplift. The surface topography in the area of 1100 × 1100 mm, including the uplifted area and a part of the surrounding area of deposition, was measured by a laser point gage at 5-mm intervals along section lines 1 cm apart and converted to 10 × 10 mm gridded data for the analysis. Within the measured 1100 × 1100 mm area, the central 600 × 600 mm (uplifted) area is the main focus of this study. Four runs (1, 2, 3, and 4), which lasted 582–1350 h, were performed with constant uplift at different rates (ca. 5.1, 1.3, 0.5 and 0.2 mm/h, respectively). These conditions are summarized in Table 1.

2.2. Development of experimental landforms

2.2.1. Run 1 (with uplift at about 5.1 mm/h for 61 h)

As the uplift-generating device pushed up the square prism of the mixture of fine sand and kaolinite (about 2.54 mm every 30 min), a

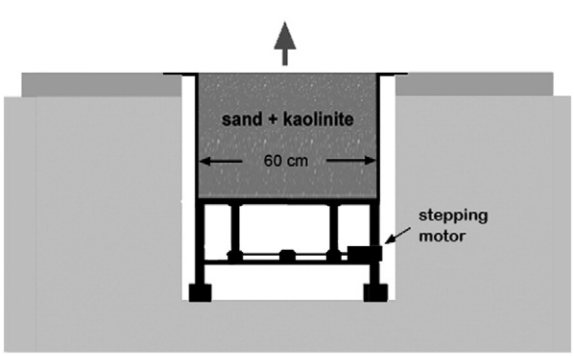

Fig. 1. Schematic illustration showing the experimental setting with the uplift-generating device.

square sand mound emerged from the ground surface under rainfall of about 38 mm/h. Small, shallow grooves appeared and extended from the mound edges after the surface was uplifted about 5 mm. Relatively deep and narrow canyon-type valleys then rapidly grew headward as the mound was being uplifted. Small-scale slope failure soon started to occur on the mound edges and valley sides after the original surface had risen about 30 mm. Slope failure on the valley sides rapidly widened the valleys and masked the development of valley systems. As the mound was further uplifted, slopes grew and large slope failures (slumps) started to occur repeatedly and encroached into the remaining plateau areas. By the end of the uplift (61 h), a massive mountain-like topography had developed with a small part of the initial flat surface surviving at the summit. This flat surface disappeared at the resumption of rainfall immediately after the measurement: the mountain had probably grown higher than a certain limit and been ready to collapse at the occurrence of a triggering event such as a temporary halt in the rainfall. The limiting height is considered to be determined by the strength of the material, the rainfall intensity, and the width of the deposition area, regardless of the uplift rate. Unfortunately, the uplift-generating device reached its limit of about 310 mm in this run at 61 h and could not generate further uplift. After uplift had ended, the mound was eroded and lowered rapidly. Slope failures dominated at first, but fluvial erosion gradually took over as relief decreased. The surface became very low and flat at the end of the run (710 h). Block diagrams (Fig. 2) roughly show the changes in topography with time.

The maximum height (*zmax*: average of the 5 highest points in the uplifted area) increased with uplift until uplift had ceased (Fig. 3). Erosion apparently did not match the uplift at this high rate. The average height of the uplifted area (*zmean*) also increased during uplift but the rate of increase slowed down around 30 h when large slope failures (slumps) started to occur. After the uplift had ended, the average height decreased exponentially. The minimum height (*zmin*: average of the lowest 5 points in the uplifted area) also increased throughout the uplift though at a lower rate, reflecting the rapid deposition of sediments in the area surrounding the uplift area.

2.2.2. Run 2 (with uplift at about 1.3 mm/h for 270 h)

The development of small shallow grooves at the mound edges became distinguishable around 4 h, after the surface had been raised about 5 mm by the uplift (ca. 0.42 mm every 20 min). Some of these grooves then grew into valleys; but these valleys were wider and shallower than those in run 1, and the development of valley systems was somewhat indistinct. Slopes emerged in places and became high enough to cause small slope failures after the initial surface had risen about 30 mm (around 25 h). Relatively large slope failures (slumps) started to occur later at around 60 h. A remnant of the initial flat surface was still observable around 142 h at a height of about 175 mm. A mountain-like topography developed, but it was not as high and massive as in run 1. The peaks were separated with the highest one at the center (Fig. 4). After uplift ended at 270 h, hills were eroded rapidly and a relatively flat surface with a scattering of low hills developed at the end of the run (Fig. 4)

The average height (*zmean*) increased with uplift at first (up to 14 h), but the rate of rise gradually decreased, and it seemed to level off at height of about 95 mm in 238–256 h (Fig. 5). After the uplift ceased at 270 h (when the uplift device reached its limit, ca. 338 mm in this run), average height decreased exponentially toward the end (646 h). The maximum height (*zmax*) increased parallel to the uplift, but around 142 h, it started to oscillate with an upper limit at about 200 mm while uplift continued (Fig. 5). After the close of uplift, maximum height decreased continuously. The minimum height (*zmin*) showed a trend of change similar to that of average height but at a lower rate.

2.2.3. Run 3 (with uplift at about 0.5 mm/h)

Small shallow grooves appeared at the mound edges around 10 h, after the original surface was uplifted about 5 mm (ca. 0.25 mm every 30 min). Some of the grooves grew into valleys. These valleys were