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# EFFECTS OF UPLIFT ON THE DEVELOPMENT OF EXPERIMENTAL EROSION LANDFORM STARTED WITH A FLAT-TOPPED SQUARE SAND MOUND

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**abstract**

Two runs of rainfall erosion experiment (one with and another without uplift) are conducted to see the effect of uplift on the development of experimental erosion landform started with a flat-topped square mound. In the first stage of erosion, valley incision and the development of a valley system proceed rapidly regardless of the uplift. The uplift then works to increase the surface relief, while the accelerated erosion keeps the average height at nearly the same level against the uplift. This suggests that the flux steady-state can be achieved while mountains are growing. The ridge tops, where the erosion is not accelerated by the uplift, move up with the uplift, while the accelerated erosion on main valley floors keeps the lowest elevation despite the uplift. As a result, overall relief increased with uplift. The increased sediment supply with uplift encourages the development of alluvial fans, which controls the local base levels, and causes some rise of lower valley floors. The residuals of the increased relief and raised lower valley floors remain long after the end of uplift. The identical changes of *H'* in both runs indicate the lack of significant effect of the uplift on the relief characteristics. The uplift does not change the manner of landform development with time, but it increases the magnitude of surface relief throughout the process.

## 1 Introduction

The development of erosional landforms (*i.e.* mountain topography), or in the broader sense the evolution of landforms, which is considered to be the function of erosion and uplift, has been hardly a main subject of geomorphologic studies for a long time, although erosional landforms make up the major part of the Earth's surface and were a main subject of geomorphology in the past, before the middle of the 20$^{\text{th}}$ century (*cf.* Chorley *et al.*, 1984). Most evidence was removed by erosion, and one often has to make up a story of landform development from pure speculation. Recently, however, with the development of digital maps, studies on the evolution of large scale mountain topography, especially studies using digital elevation models (DEMs), have become increasingly popular (*cf.* Burbank, 1992; Pazzaglia and Knuepfer, 2001). Numerical models are built and checked on the basis of DEMs (*e.g.* Gilchrist *et al.*, 1994). Nonetheless, a series of evidences that records the actual landform change is still required to corroborate the models, because numerical models usually appear only to validate conjectures by geomorphologists (*e.g.* Hasbargen and Paola, 2000). River

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terraces and longitudinal profiles of rivers are often employed as the evidence documenting long-term landform development from the view point of the interaction between erosion and uplift (*e.g.* Merritts and Vincent, 1989; Burbank *et al.*, 1996; Pazzaglia and Brandon, 2001) sometimes with the help of DEMs (*e.g.* Schoenbohm *et al.*, 2004), but the lack of evidence is still undeniable. Rainfall erosion experiments, or physical models, may be the only tool that can provide solid information in time sequence for estimating the manner of landform evolution. Although the experiments are not a reproduction of what happens in real mountain areas, experimental landforms should be considered as a prototype among whole varieties of different landforms. Conducting rainfall erosion experiments is not straightforward, however. Not only the technical difficulties but also numerous factors involved, many of which are difficult to control or measure, discourage researchers from performing rainfall erosion experiments. Small numbers of rainfall erosion experiments still have been conducted despite these difficulties (*cf.* Schumm *et al.*, 1987); however, no rainfall erosion experiments have been done with adding another complicated factor, uplift, except for a few trials. Hasbargen and Paola (2000) conducted an experiment using an oval tank with a motor-controlled gate at the outlet. Dropping the gate at a slow rate imitates the uplift. The possibility they pointed out from the results, that current numerical models may be too static, is reasonable, but their experimental setting, their dropping gate as a substitute of uplift, the material used, the duration of rainfall and so on, need to be examined through further trial and error. I have been conducting a series of rainfall erosion experiments, in which miniature erosion landforms develop with artificial rainfall on a square mound of a fine sand and clay mixture. These experimental miniature erosion landforms were analyzed as self-affine fractal surfaces (Ouchi, 1996), and the effects of clay content (permeability) and rainfall intensity on the characteristics of experimental erosion landforms were ascertained (Ouchi and Matsushita, 1997; Ouchi, 2001). This paper reports the results of rainfall erosion experiments, in which another important factor, uplift, is introduced, and discusses the effect of uplift on the development of experimental erosion landforms. The experiments are not a reproduction of real landform evolution, but they will hopefully provide some ideas for better understanding the development of mountain topography.

## 2 Experimental setting and procedure

A flat-topped square mound made of a mixture of fine sand ($D_{50} \approx 0.18$ mm) and kaolinite is built on the uplift-generating device buried under the ground (Fig. 1). The ratio of sand and kaolinite is 10:1 by weight and the average permeability of the mound is about $3.1 \times 10^{-4}$ cm/s. The dimension of the mound is approximately $90 \times 90 \times 13$ cm on the ground and nearly the same amount under the ground. Miniature erosion landforms develop on the mound when artificial rainfall is applied at an average of 38 mm/hour in average (Fig. 2). Rainfall continues for 255 hours in both Run A (with uplift) and Run B (without uplift) with breaks for measurements. In Run A, the uplift starts at the beginning and continues for 128 hours, once ($1.6 \sim 0.2$ mm) an hour. No uplift is applied in Run B to determine the effect of uplift in Run A by comparing the results. Generating slight amounts of uplift by controlling the hydraulic jack used in the uplift device is very difficult; and therefore, the rate of uplift changed a little with time. The surface topography of the mound is measured repeatedly with a point gage along 77 cross section lines spaced at 1 cm intervals on the inner $76 \times 76$ cm area of the mound surface while the rainfall is discontinued. All the points considered to indicate the surface topography are measured and converted to $76 \times 76$ cm gridded data for the analysis.

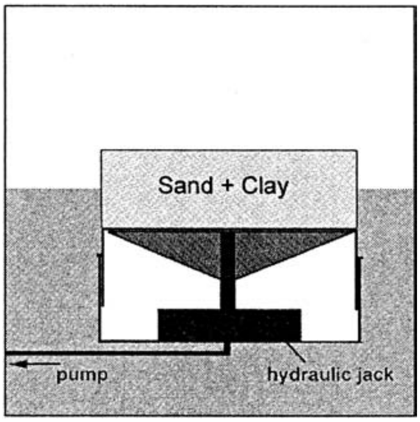


Fig. 1 Schematic diagram showing the setting of the mound and the uplift generating device.

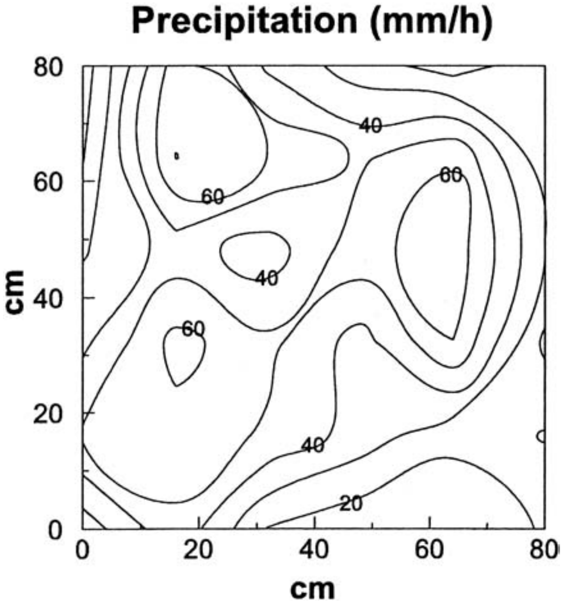


Fig. 2 Distribution of average precipitation.

## 3 Development of experimental miniature erosion landforms

Figures 3 and 4 show the development of erosion landforms in both Runs with block diagrams, and Figures 5 and 6 show hypsometric curves of surface topography. Erosion by surface runoff starts shortly after the beginning of experiments, and the valley incision into the flat surface from the edges of the mound is clear within 1 hour (Figs. 3, 4, 5, and 6). In the first stage of the experiments ($\sim$ 7 hours of rainfall), valley incision and development of the valley system proceed rapidly on the flat surface in both Runs, and this appears in the sharp drop of the average height (Figs. 7 and 8). The rapid valley incision into the flat-topped square mound apparently dominates in this stage. The mountain-like topography then develops and culminates during 15$\sim$63 hours of rainfall in both Runs. The hypsometric curves change from convex up to concave up sometime in 15$\sim$31 hours in both Runs (Figs. 5 and 6), indicating the expansion of lower flat areas by lateral erosion. Landforms look very

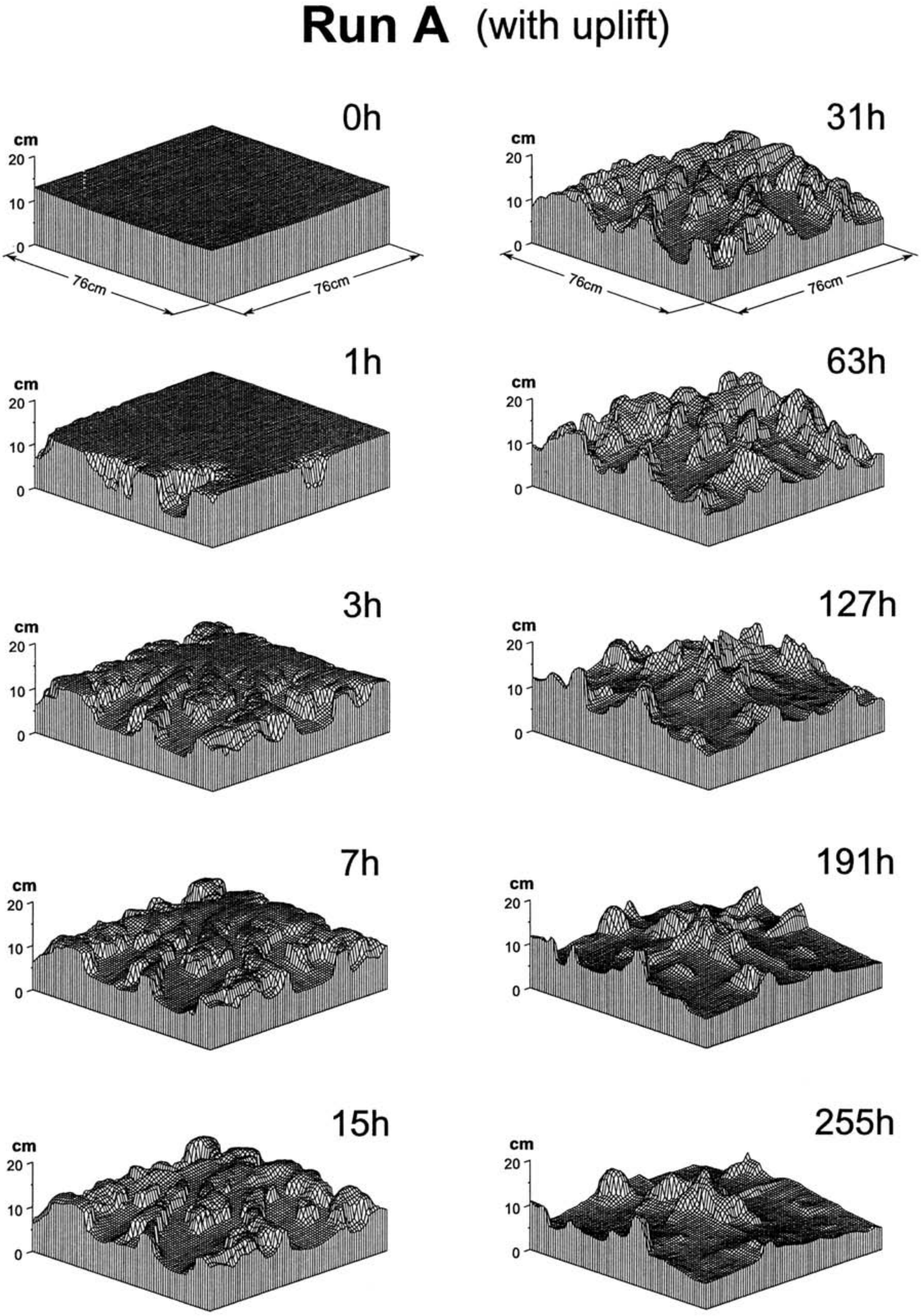


Fig. 3 Block diagrams showing the erosion landforms measured in Run A (with uplift).

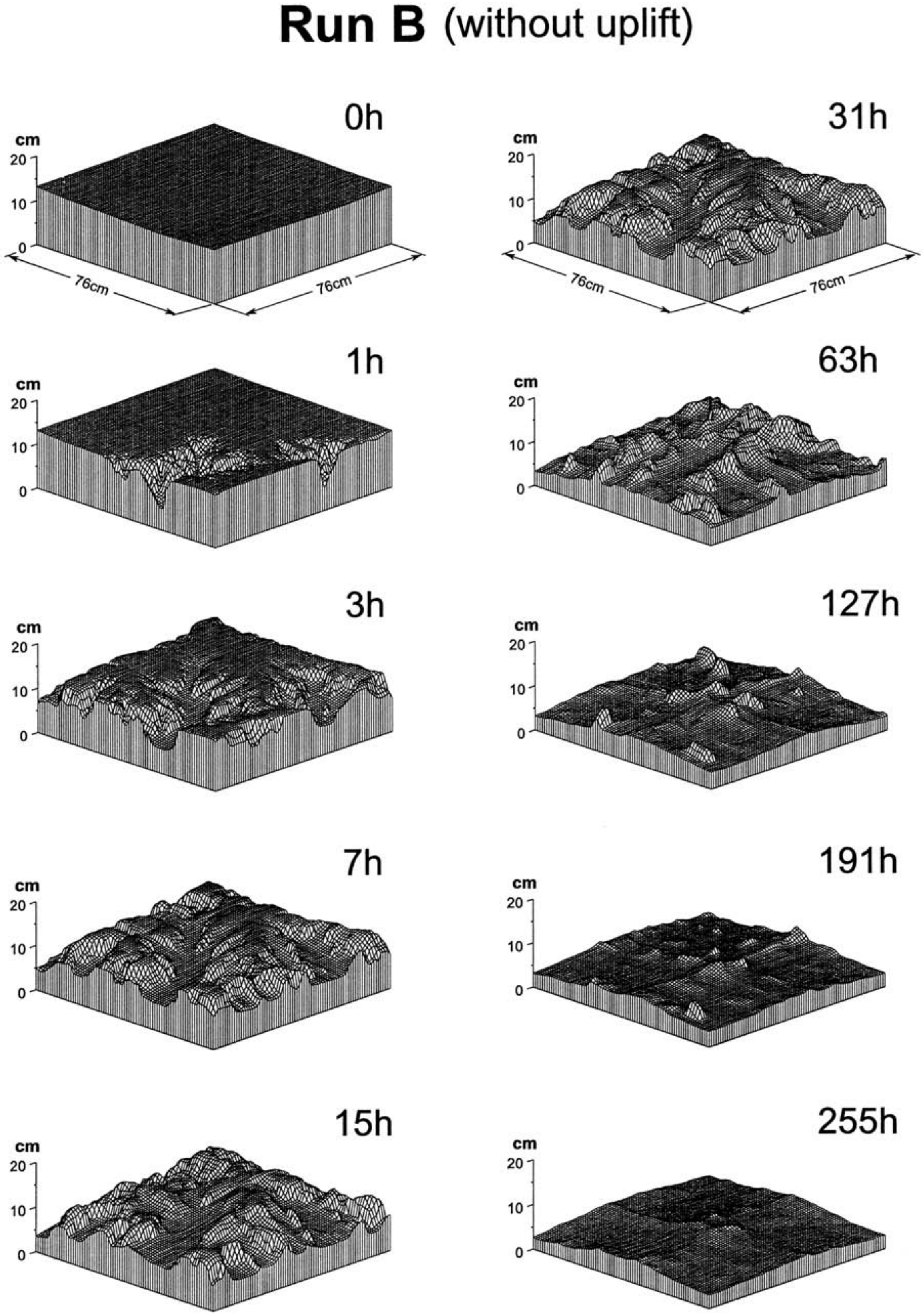


Fig. 4 Block diagrams showing the erosion landforms measured in Run B (without uplift).

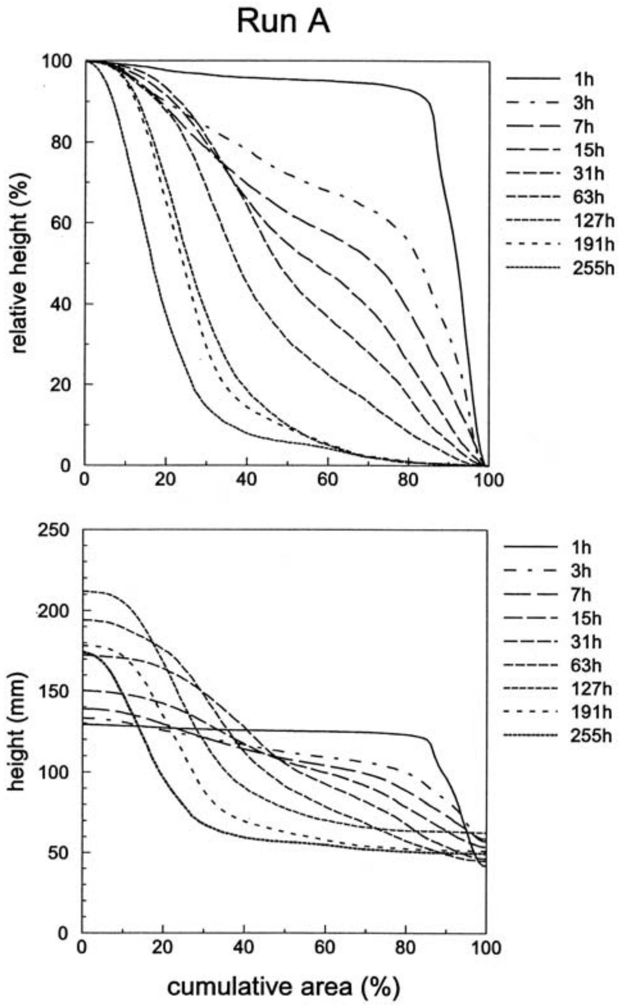


Fig. 5 Hypsometric curves (upper) and absolute hypsometric curves (lower) of Run A.

similar in both Runs except for the magnitude of relief. The upper part of the landform (ridges), grows higher than the incipient surface with the uplift in Run A, while the lower part continuously goes down except for the lower end areas, as shown by the absolute hypsometric curves in Figure 5. Although the ridges decrease their height after the uplift, some ridge-like rises still exist at the end of Run A (255 hours)(Fig. 3). In contrast, almost the entire surface lowers continuously in Run B, the lower half first and then the upper half (Fig. 6), and a peneplain-like flat topography appears at the end (Fig. 4). Average height (*zmean*) in Run A decreases rapidly in the first stage, but stays at nearly the same level by the end of the uplift (128 hours) and then decreases slowly (Fig. 7). In Run B (without uplift), *zmean* decreases exponentially throughout the experiment (Fig. 8). At the end of experiments the volume of material eroded from the measured area amounts to about $9.1 \times 10^4$ cm$^3$ and $5.0 \times 10^4$cm$^3$ in Runs A and B, respectively. The maximum height (*zmax*) in Run A increases nearly as much as the uplift, while the minimum height (*zmin*) increases only a little, much less than the amount of uplift (Fig. 9). As a result, the overall relief increases with the uplift. These changes in the maximum and minimum heights indicate that the major valleys, which developed in the first stage of erosion (~7 hours), can mostly keep their bottom height against the uplift, while

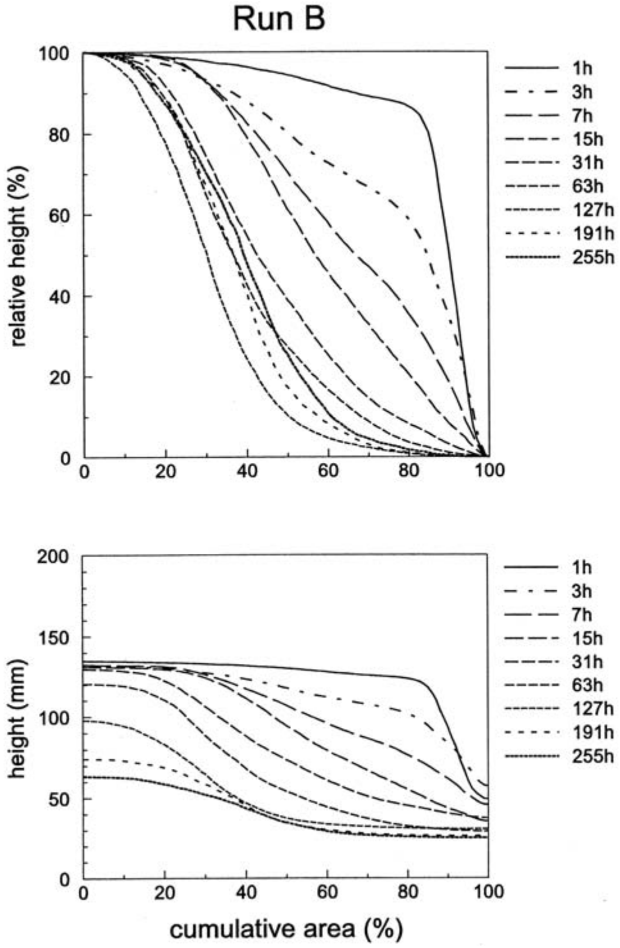


Fig. 6 Hypsometric curves (upper) and absolute hypsometric curves (lower) of Run B.

the ridge tops move up with the uplift (Fig. 10). In Run B, on the other hand, the maximum height gradually decreases throughout the experiment, and the minimum height stays at nearly the same height after the rapid decrease in the first stage. The standard deviation of heights within the area of $10 \times 10$ cm (*Zi*), which represents the degree of local relief, increases rapidly in the first stage of erosion in both Runs (Fig. 11). The local relief (*Zi*) stops its rapid increase by 7 hours and starts decreasing after 31 hours in Run B. In Run A (with uplift), *Zi* increases continually by 63 hours with a slower rate after the rapid increase by 7 hours and starts decreasing. The value of *Zi* comes down from the peak of 18.7 mm at 63 hours to 11.7 mm at 127 hours in Run A, while the maximum height goes up from 218.4 mm to 238.1 mm. *H'*, which is a self-affine parameter of surfaces and expresses the relief characteristics (Matsushita and Ouchi, 1989; Ouchi and Matsushita, 1992), changes almost identically in Runs A and B (Fig. 12). This indicates that valleys and ridges develop in a similar way in both Runs except for the magnitude of relief. *H'* drops from a value close to 1.0 to a value around 0.5, which indicates a random surface topography, by 7 hours, and starts gradual increase from 31 hours in both Runs. This change in *H'* is considered typical for this experimental setting (Ouchi and Matsushita, 1997). The time, 31 hours, is the time when the hypsometric curve starts developing a clear concavity (Figs. 5 and 6). The hypsometric curves do not show the area-altitude relationship for one drainage area (no probable reverse S curves), but still indicate that planation by

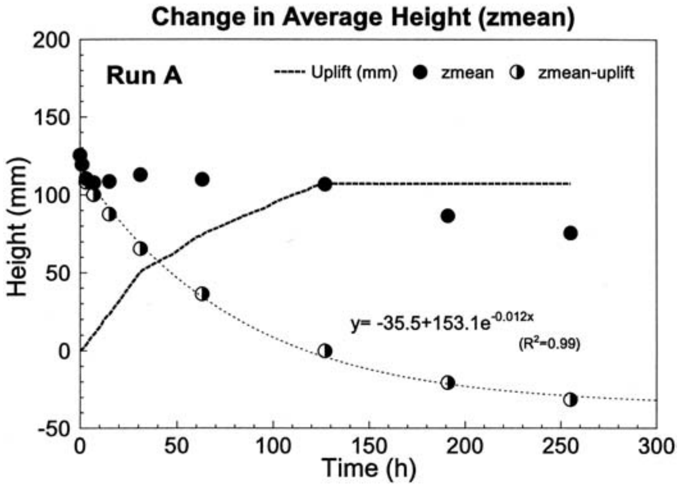


Fig. 7 Changes of average height (*zmean*) in Run A. Cumulative amount of uplift is also shown in the graph.

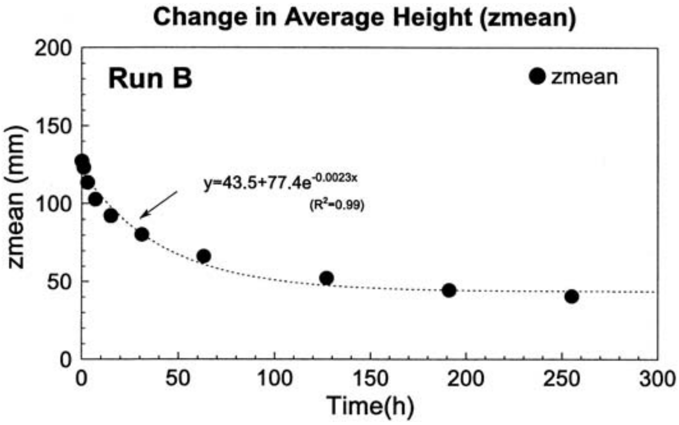


Fig. 8 Changes of average height (*zmean*) in Run B.

lateral erosion becomes dominant from lower areas, as also shown in block diagrams (Figs. 3 and 4).

## 4 Effects of uplift on the development of experimental erosion landforms

Ouchi and Matsushita (1997) reported the different development types of experimental erosion landforms due to the difference in clay contents and rainfall intensity. Runs A and B use the same material and rainfall, and the uplift in Run A is the only intended difference between these two Runs. After the first stage of the experiments (∼ 7 hours), when the rapid valley erosion into the flat surface dominates, the uplift works to keep the average height (*zmean*) at nearly the same level in Run A (Fig. 7), while the average height continues to decrease exponentially in Run B (Fig. 8). The average height in Run A, however, shows a clear exponential decrease when the amount of uplift is deducted (Fig. 7). This exponential decrease may reflect erosion at a rate sufficient to cancel the uplift, because the height increase by the uplift is nearly exponential. However, even if the uplift had been controlled in a constant rate, the decrease in average height after the deduction of uplift would be somewhat exponential, rather than linear. Judging from the average height change without uplift in Run B (Fig. 8), the nature of the average height decrease is certainly exponential. The amount

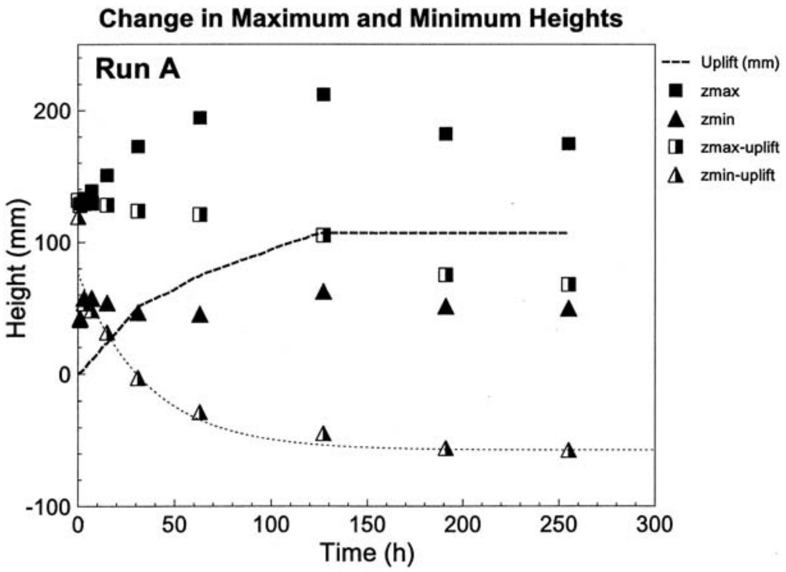


Fig. 9 Changes of maximum (*zmax*) and minimum (*zmin*) heights in Run A. Values after the deduction of uplift are also shown in the graph. The equation of the regression line for *zmin* after the deduction of uplift is $y = -57.5 + 133.3e^{0.028x}$.

of average height decrease in Run A after the deduction of uplift is larger than that of Run B, and this means that the uplift apparently accelerates the erosion of the mound. On the other hand, the change in the maximum height (*zmax*) in Run A becomes almost identical with the *zmax* change in Run B when the amount of uplift is deducted (Figs. 9 and 10). The uplift seems not to affect the degradation of ridges, and ridge tops are simply uplifted with the normal slow degradation. The minimum height (*zmin*), which represents the bottom height of the main valley, shows a similar change in both Runs (Figs. 9 and 10). It decreases rapidly in the first hour but does not change much after the first stage in both Runs. The minimum height in Run A after the deduction of uplift shows exponential decrease reflecting the incision compensating the uplift (Fig. 9). The valley incision is considered rapid enough to cancel the uplift. The minimum height in Run A, however, becomes slightly higher at the end of the uplift, indicating some rise of valley floors as an effect of the uplift. The absolute hypsometric curves in Figure 5 also show the rise of lower part at 127 hours. The increased volume of material carried out from the mound by the accelerated erosion due to the uplift in Run A promotes the development of alluvial fans around the mound. While the erosion on the alluvial fans become apparent after 31 hours in Run B, deposition is still active on some alluvial fans at the end of uplift (127 hours) in Run A. Alluvial fans around the mound grow larger and higher in Run A. The increased and prolonged sediment supply onto the alluvial fans due to the uplift makes the floors of major valleys slightly higher. The development of alluvial fans ceases with the uplift, but they are not eroded so much after that. The value of *zmin* in Run A remains larger than that of Run B at the end of experiments. The minimum height, or the lowest valley floor height, is considered to be determined by the base level of erosion, namely the ground height; however, the development of alluvial fans appears to control it in the experiments. Alluvial fans seem to set the local base level of erosion for the upstream erosion area. Despite this slight increase in valley bottom height, the overall relief continues to increase in Run A due to the increase of the maximum height by the uplift. The value of *Zi* ceases increasing by 7 hours and starts decreasing after 31 hours in Run B. In Run A, *Zi* increases continually by 63 hours with a slower rate and then decreases in a

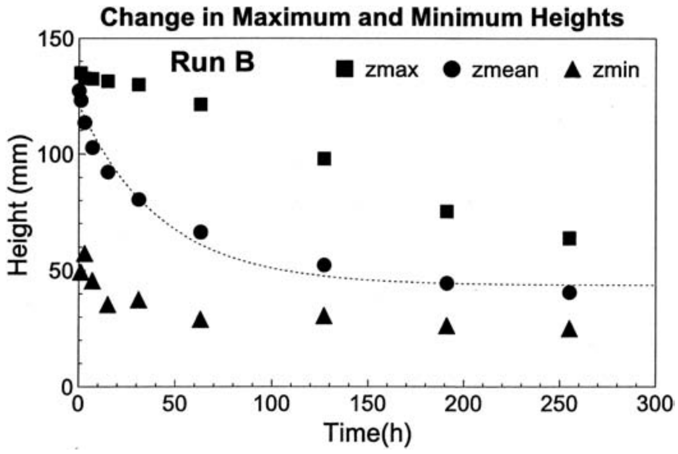


Fig. 10　Changes of maximum (*zmax*) and minimum (*zmin*) heights in Run B. Values after the deduction of uplift are also shown.

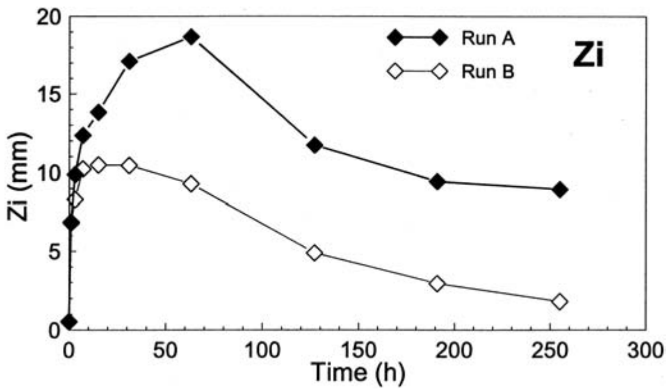


Fig. 11　Changes of average standard deviation of elevation in a 10 × 10 cm square (*Zi*) in Runs A and B.

similar way to that in Run B. This results in the difference in *Zi* (about 7 mm) at the end of two Runs (Fig. 11). Local relief represented by *Zi* indicates the change similar to the overall relief, except for the time period from 63∼127 hours in Run A (Fig. 11). During this time period, the value of *Zi* comes down from the peak of 18.7 mm at 63 hours to 11.7 mm at 127 hours, while the maximum height goes up from 194.4 mm to 214.1 mm. In Run B *Zi* reaches its peak at 15 hours and then decreases from 31 hours. The time at which *Zi* reaches the peak (31∼63 hours in Run A and 15∼31 hours in Run B) is in the time period when the mountain topography reaches its maximum (Figs. 3 and 4) and hypsometric curves start to develop a concavity (Figs. 5 and 6). The local relief seems to start decreasing earlier than the overall relief regardless of the uplift, but in Run A the process of relief decrease (both local and overall) is delayed, probably by the effect of uplift. The identical changes of *H'* in both Runs (Fig. 12) indicate the lack of significant effect of the uplift on the relief characteristics. The increased relief by the uplift leaves some ridges even at the end of Run A (255 hours), while a peneplain-like topography appeared at the end of Run B. The manner of decrease in *zmax* and *Zi* after the uplift creates the impression that the increased relief as the result of uplift will never reach the level of peneplain.

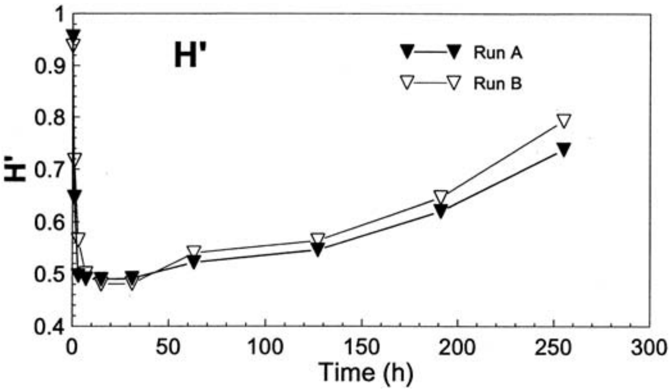


Fig. 12 Changes of parameter *H'* in Runs A and B.

## 5 Summary and conclusions

Two runs of rainfall erosion experiment (Runs A and B, with and without uplift, respectively) are conducted to see the effect of uplift on the development of experimental erosion landform. The experimental condition is kept almost the same through these two Runs except for the uplift. The experiments starts with similar flat-topped square mounds made of a mixture of fine sand and kaolinite. In the first stage of erosion (∼7 hours) a valley system develops with rapid valley incision into the flat surface, and this process dominates regardless of the uplift (Figs. 3 and 4). After the first stage in Run A, the valley erosion is accelerated (compared with Run B of no uplift) enough to keep the average height (*zmean*) at almost the same level against the continuous uplift (Figs. 7 and 8). However, the ridge tops represented by *zmax*, where the erosion is much slower, move up nearly the same amount as the uplift, while the floor of the main valley, represented by the minimum height (*zmin*), shows only a slight increase with the uplift (Fig. 9). The change in maximum height in Run A becomes almost identical with that in Run B when the amount of uplift is deduced. This means that the uplift does not affect the manner of ridge degradation. The uplift does not lift up the whole mound but works to increase the surface relief. The uplift apparently causes the difference in relief (both local and overall) as shown by *zmax*, *zmean* and *Zi* (Figs. 9, 10 and 11), although no other effects of uplift are clear. The local relief (*Zi*) starts to decrease while the mound is still uplifted and the maximum height is increasing. This suggests that the surface planation after the development of mountain topography starts from the lower part regardless of the uplift. The identical changes of *H'* in both Runs (Fig. 12) indicate the lack of significant effect of the uplift on the relief characteristics.

The results of experiments indicate that the main effect of uplift on the development of experimental erosion landforms is increasing the surface relief. The comparison of Run A (with uplift) and Run B (without uplift) suggests that the development of erosion landform proceed in a similar way on a flat-topped mound regardless of uplift, if the rainfall intensity, the material and the dimension of mound are similar. Uplift accelerates the erosion on valley floors and lifts up ridges, and as a result the surface relief increases. Mountains grow higher with uplift and the relief remains longer after the end of uplift, while the other characteristics of surface topography remain similar. Except in the early stage of erosion, in which the development of a valley system with rapid valley incision dominates, uplift works to increase the surface relief while the accelerated erosion keeps the average height at nearly the same level. This means that the flux steady-state (Pazzaglia and Knuepfer,

2001) can be achieved while mountains are growing. The increased sediment supply by uplift, on the other hand, encourages the development of alluvial fans, which possibly controls the local base levels for upstream erosion areas, and causes some rise of lower valley floors. An uplifted surface may be able to stay higher for a longer time. The uplift probably does not change the manner of landform development with time, but it increases the magnitude of surface relief throughout the process.

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## References

Burbank, D. W., 1992, Characteristic size of relief: Nature, v.359, p.483–484.

Burbank, D.J., Leland, J., Fielding, E., Anderson, S., Brozovic, N., Reid, M., and Duncan, C., 1996, Bedrock incision, rock uplift, and threshold hillslopes in the northwestern Himalayas: Nature, v.379, p.505–510.

Chorley, R. J., Schumm, S. A., and Sugden, D. E., 1984, Geomorphology: Methuen, London, 605p.

Gilchrist, A. R., Summerfield, M. A., and Cockburn, H. A. P., 1994, Landscape dissection, isostatic uplift, and the morphologic development of orogens: Geology, v.22, p.963–966.

Hasbargen, L. E., and Paola, C., 2000, Landscape instability in an experimental drainage basin: Geology, v.28, p.1067–1070.

Matsushita, M., and Ouchi, S, 1989, On the self-affinity of various curves: Journal of the Physical Society of Japan, 58, 1489–1492.

Merritts, D., and Vincent, K. R., 1989, Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Mendocino triple junction region, northern California: Geological Society of America Bulletin, v.101, p.1373–1388.

Ouchi, S., 1996, Fractal analysis on the miniature erosion landform generated by artificial rainfall: Geographical Report of Tokyo Metropolitan University, 31, 97–103.

Ouchi, S., 2001, Development of miniature erosion landforms in a small rainfall erosion facility, in Anthony, D. J, Harvey, M. D., Laronne, J. B., Mosley, M. P., eds., Applying Geomorphology to Environmental Management: Water Resources Publications, Fort Collins, CO, p.79–92.

Ouchi, S., and Matsushita, M., 1992, Measurement of self-affinity on surfaces as a trial application of fractal geometry to landform analysis: Geomorphology, v.5, p.115–130.

Ouchi, S., and Matsushita, M., 1997, Morphological characteristics and evolution of miniature erosional landforms generated by artificial rainfall: Journal of the Institute of Science and Engineering, Chuo University, v.3, p.67–80.

Pazzaglia, F. J., and Knuepfer, P. L. K., editors, 2001, Steady-state organ: Preface of the special issue of the American Journal of Science, v.301, p.ix–xi.

Pazzaglia, F. J., and Brandon, M. T., 2001, A fluvial record of ling-term steady-state uplift and erosion across the Cascadia Forearc High, western Washington state: American Journal of Science, v.301, p.385–431.

Schoenbohm, L. M., Whipple, K. X., Burchfiel, B. C., and Chen, L., 2004, Geomorphic constraints on surface uplift, exhumation, and plateau growth in the Red River region, Yunnan Province, China:

Geological Society of America Bulletin, v.116, p.895–909.
Schumm, S. A., Mosley, M. P., and Weaver, W. E., 1987, Experimental fluvial geomorphology: Wiley, New York, 413p.