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Development of Mountains and Alluvial Fans in Japan, Taiwan, and the Philippines

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Abstract: In Japan, where uplift and denudation have been active during the Quaternary, the growing stage of mountains has been divided into the earliest, early, younger-middle, older-middle, and later substages. In this study, relationships have been discussed quantitatively between the development stage of mountains and alluvial-fan existence and size in tectonically active Japan, Taiwan, and the Philippines. Among relief ratio, drainage-basin area, temperature, and precipitation, relief ratio was determined to be the most important variable for predicting the existence of alluvial fans for rivers with source areas greater than 100 km². As mountains pass through their development stages from earliest to later, their relief ratios increase and the number and size of alluvial fans increase, especially from the older-middle substage. In drainage basins over 100 km², the relief ratio of 30‰ is estimated to be an important threshold for the existence of an alluvial fan. In the older-middle substage almost all rivers have high relief ratios greater than 30‰, while only 63% of the rivers show such high relief ratios in the younger-middle substage. In addition, the size of alluvial fans in drainage basins with relief ratios greater than 60‰ is larger than the size with relief ratios lower than 60‰. The percentage of the rivers with relief ratios over 60‰ in the older-middle substage is markedly higher than that in the younger-middle substage. In this way, the increase in relief ratios (steeper riverbeds) beginning in the older-middle substage provides good conditions for the development and increased size of alluvial fans. Furthermore, the tropical climate in the Philippines, which seems to be disadvantageous for the development of alluvial fans in general, does not necessarily result in smaller alluvial fans when alluvial fans do develop.

Key words: alluvial fan, alluvial-fan distribution, development of mountains, Japan, Taiwan, Philippines

Introduction

Channel sediment in tropical climates is generally fine due to strong chemical-weathering (Peltier 1950). As a result, tropical climates appear to be unfavorable for alluvial-fan formation. Indeed, in drainage basins greater than 100 km² in Japan, Taiwan, and the Philippines, higher temperatures have been shown to be disadvantageous for the development of alluvial fans during the Holocene (Saito 1995). However, relief ratio (height difference between the elevation of a peak and that of a valley mouth divided by drainage-basin length: Schumm 1956) has been demonstrated to be more important than temperature in determining alluvial-fan distribution (Saito 1995, 1997a).

Relief ratio is considered to correlate with the altitude dispersion of a drainage basin (Saito 1989a). On the basis of the dispersion and the mean altitude, Japanese mountains are in various substages of the growing stage (Ohmori 1978). In the advanced middle substage, rates of increase in both the mean altitude and the dispersion are greatest. Saito (1986a) has indicated that alluvial-fan existence and size increase markedly in the advanced middle substage in Japan. In this study, relationships between the development stage of mountains and alluvial-fan existence and size have been discussed quantitatively not only for Japan but also for Taiwan and the Philippines.

Distribution of Alluvial Fans

Collection of alluvial fan data

Alluvial fans are distributed throughout tectonically active Japan, Taiwan, and the Phil-

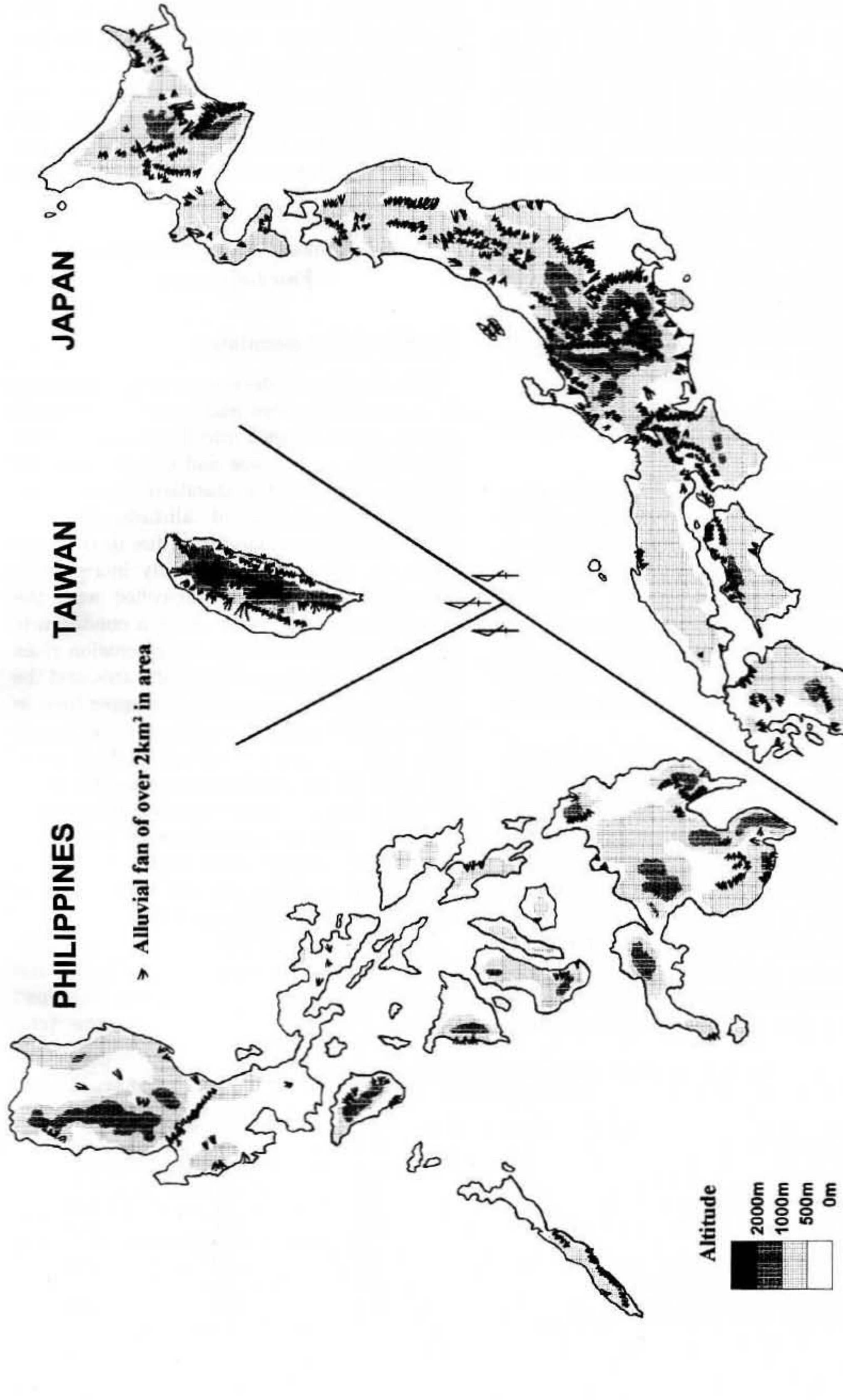

Figure 1. Distribution of alluvial fans in Japan, Taiwan, and the Philippines.
Compiled from Saito (1993, 1996)

ippines. Distributions of alluvial fans have been mapped in Japan (Murata 1935; Toya et al. 1971; Saito 1988), in Taiwan (Tomita 1972; Saito 1993; Chan 1997), and in the Philippines (Saito 1996). In this study, an alluvial fan is defined as a semi-conical landform whose area exceeds 2 km^2 with a mean radial-slope greater than 2‰. For Japan, alluvial fans were located and fan areas were measured on 1 : 25,000 topographic maps with 10 m contour intervals, while in Taiwan and the Philippines, 1 : 50,000 maps with 20 m contour intervals were used. There are 490 rivers with alluvial fans in Japan, 71 in Taiwan, and 129 in the Philippines (Figure 1).

Simple comparison of fan existence among the three regions

The numbers of rivers with alluvial fans per a land area of 1,000 km^2 are 1.30 in Japan, 1.97 in Taiwan, and 0.43 in the Philippines (Table 1). The number for the Philippines is smaller than the number for Japan and Taiwan. However, this comparison is not necessarily valid, because it does not take into consideration the areal extent of mountains and plains. In general, wider plains or wider mountain ranges cause the number to be lower.

For a comparison under similar conditions, rivers with drainage basins larger than 100 km^2 were collected, using topographic maps for all the islands of the three regions (Figure 2). The percentages of rivers with alluvial fans are 26% in Japan, 58% in Taiwan, and 12% in the Philippines (Table 1). Based on this simple comparison, the percentage is the lowest in the Philippines. Although relief ratios in the Philippines are comparatively higher than those in Japan (Figure 3), the higher temperatures in the Philippines appear to limit the number of alluvial fans (Saito 1997a). On the contrary, the percentage is the highest in Taiwan where almost all rivers show relief ratios greater than 30‰ and 76% of rivers have ratios over 60‰. The high relief ratios have led to the highest percentage of alluvial-fan existence in Taiwan (Saito 1990).

Development of Mountains and Fan Existence

Development of mountains

The geomorphic development of mountains in tectonically active and intensely denuded regions can be divided into three stages on the basis of the mean value and the dispersion of altitude which is the standard deviation of frequency-distribution of altitudes (Ohmori 1978). When mountains rise due to constant uplift, the mean altitude rapidly increases at first, and denudation is intensified with the great altitude dispersion. Such a condition is defined as the first stage. Then, erosion rates begin to be in balance with uplift rates, and the mean altitude is maintained at an upper limit as long as uplift continues uniformly. In mountains with a rapid rate of uplift, the time to reach this second stage is shorter and the mean altitude is higher. When the rate of uplift declines, the mean altitude decreases. This is the third stage. These three stages have been labeled the growing, the climactic, and the declining stages (Yoshikawa 1984).

The dispersion of altitude is strongly correlated to the mean altitude of mountains and the contemporary denudation rate in Japan (Ohmori 1978). Furthermore, as the total

Table 1. Numbers of rivers with alluvial fans in the three regions

	Japan	Taiwan	Philippines
Area of a land (10^3 km^2)	378	36	300
Number of alluvial fans over 2 km^2	586	79	131
Number of rivers with the alluvial fans	490	71	129
Number of rivers with the fans per 1,000 km^2	1.30	1.97	0.43
Number of rivers with drainage basins over 100 km^2	474	50	266
Number of the large rivers with the fans	123	29	32
Percentage of the large rivers with the fans	25.9	58.0	12.0

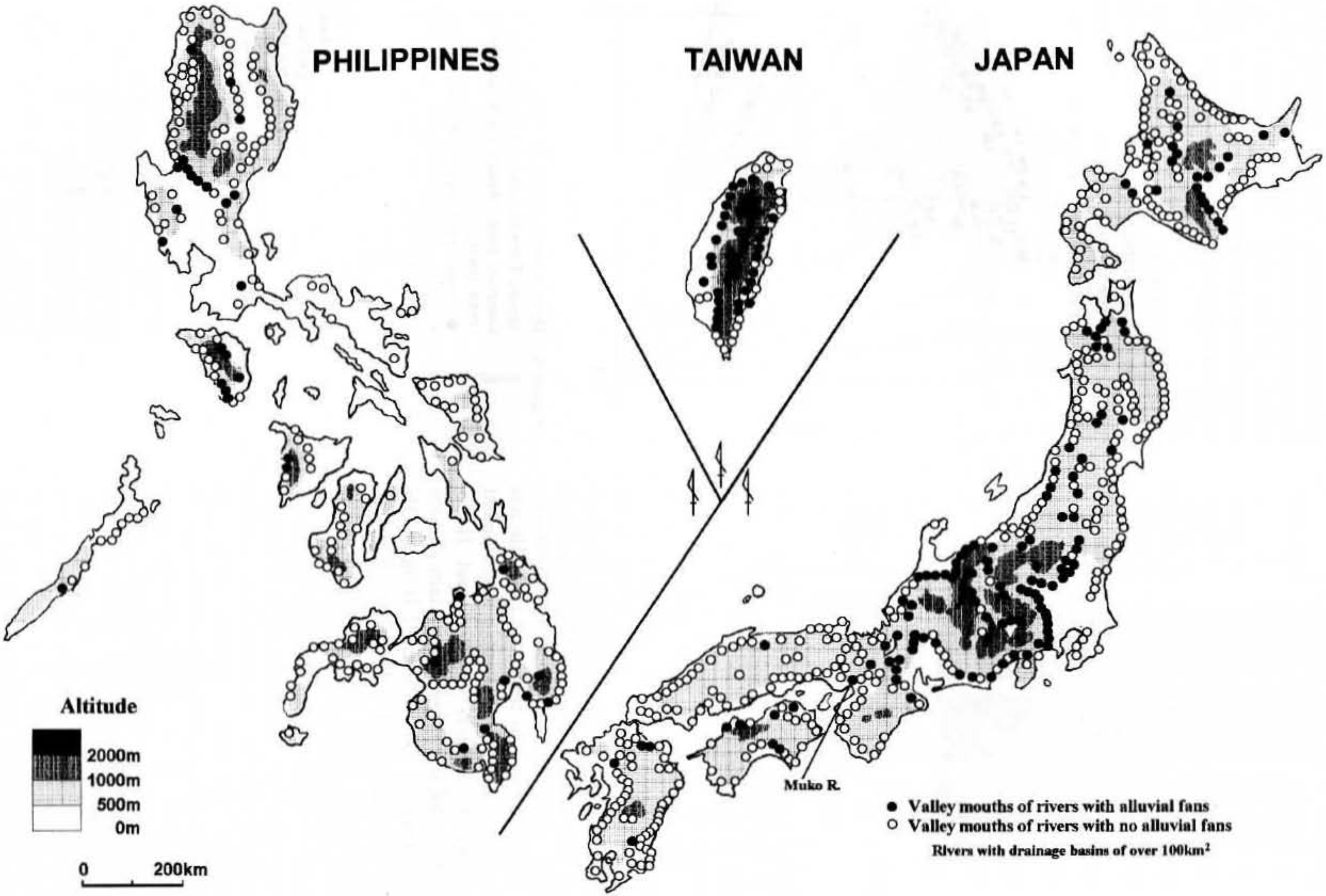

Figure 2. Distribution of valley mouths of drainage basins larger than 100 km^2 in area.

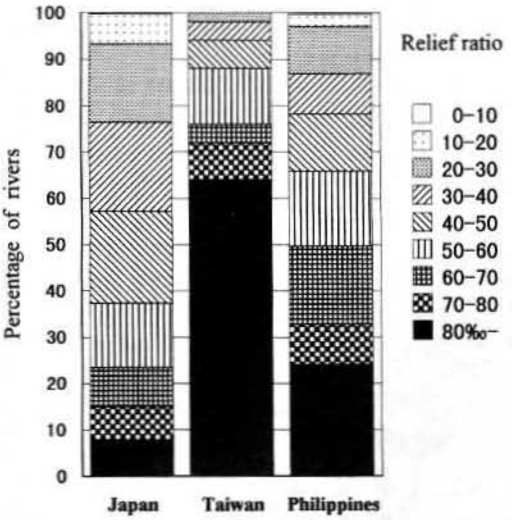

Figure 3. Relief ratios of drainage basins over 100 km² in Japan, Taiwan, and the Philippines.

amount of mountain uplift is equivalent to the sum of the mean mountain altitude and total amount of denudation, the uplift rate of each mountains could be estimated based on the mean altitude and the start age of uplift. Applying this concept to the 26 non-volcanic ranges in Japan, Ohmori (1978) estimated the hypothetical mean mountain altitude (Ho) if no denudation had happened and the upperlimit mountain altitude (Hlim) when the denudation rate becomes equal to the uplift rate. He has defined the stage of geomorphic development using two parameters, H/Hlim and H/Ho, where H is the actual mean mountain altitude (Figures 4 and 5). The values of H/Hlim and H/Ho get close to 1 and 0 with time respectively.

Figure 4 was drawn on the assumption that the initial altitude of the region was 0 m above sea level and the subsequent mountain uplift has lasted for one million years. The earliest substage is characterised as a poorly dissected peneplain. In the early substage topographic change is relatively slow. The latest early and the beginning of the middle substage were grouped into the younger-middle substage in this study. In the advanced middle substage (the older-middle substage in this study), rates of increase in both the mean altitude and the dispersion of altitude with time are the highest among the Japanese mountains. In the later substage, geomorphic change in the mountains is no longer active and maintaining equilibrium states. All the later substage mountains are located in Central Japan, where rates of uplift and denudation are very rapid (Yoshikawa 1974).

The close relations between the mean altitude and the dispersion of altitude were recognized in the 5 mountain ranges of Taiwan (Saito 1989) and in the 13 non-volcanic moun-

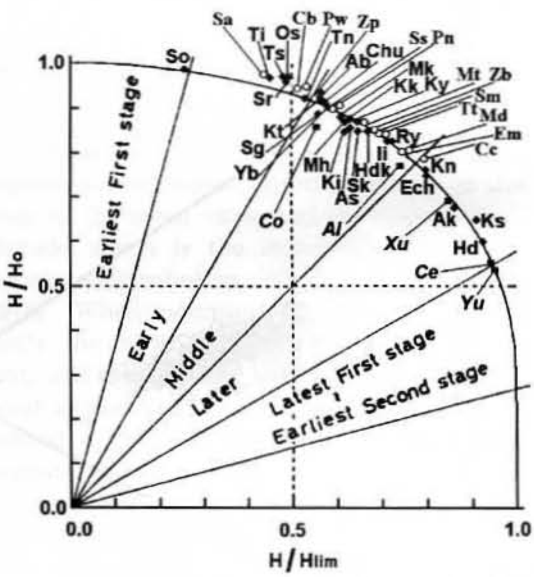

Figure 4. Development stages of mountains in Japan, Taiwan, and the Philippines.
Compiled from Ohmori (1978) and Saito (1989, 1997b)
◆: Japan. Ab: Abukuma Mts., Ak: Akaishi Range, As: Asahi Mts., Chu: Chugoku Mts., Ech: Echigo Range, Hd: Hida Range, Hdk: Hidaka Range, Ii: Iide Mts., Ki: Kii Mts., Kk: Kitakami Mts., Kn: Kanto Mts., Ks: Kiso Range, Kt: Kitami Mts., Ky: Kyushu Mts., Mh: Mahiru Mts., Mk: Mikawa Plateau, Os: Oshima Peninsula, Ry: Ryohaku Mts., Sg: Shiragami Mts., Sk: Shikoku Mts., So: Soya Hill, Sr: Shiranuka Hill, Ti: Taihei Mts., Tn: Tamba Highland, Ts: Teshio Mts., Yb: Yubari Mts.
■: Taiwan. Al: Alishan Mts., Ce: Central Mts., Co: Coastal Mts., Xu: Xueshan Mts., Yu: Yushan Mts.
○: Philippines. Cb: Cebu, Cc: Cordillera Central, Em: Eastern Cordillera of Mindanao, Md: Mindoro, Mt: Matutum Range, Pn: Panay, Pw: Palawan, Sa: Samar, Sm: Sierra Madre, Ss: Southern Sierra Madre, Tt: Tiruray Tableland, Zb: Zambales Mts., Zp: Zamboanga Peninsula

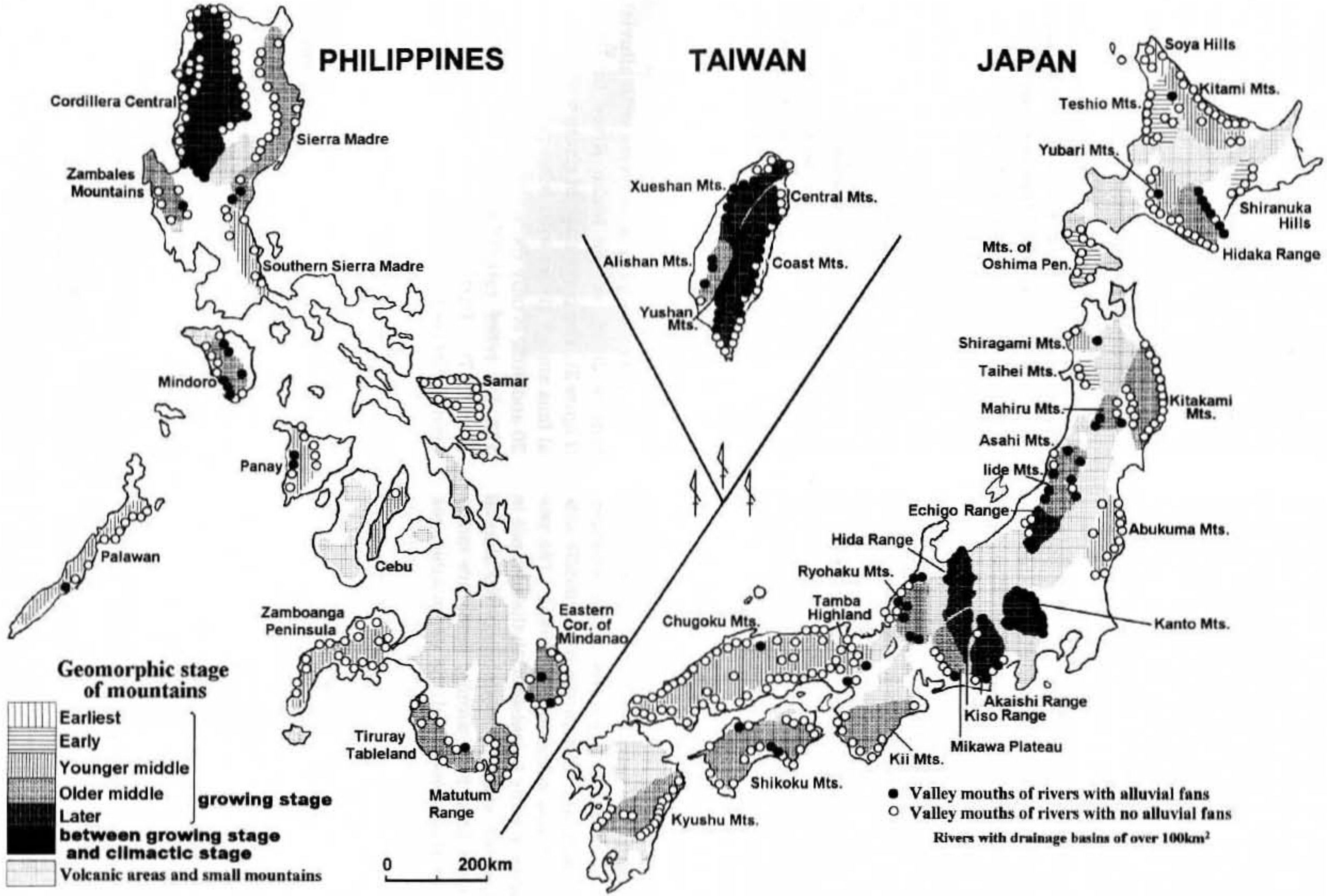

Figure 5. Development stages of mountains and distribution of alluvial fans.
Compiled from Ohmori (1978) and Saito (1989, 1997b)

tain ranges of the Philippines (Saito 1997b). Hence, the geomorphic development stages of mountains in Taiwan and the Philippines were determined using the above-mentioned method of Ohmori (1978). In general, mountains in Taiwan are in a more advanced stage of development, whereas Japanese mountains are characteristic of regions in which both mature and immature mountains coexist (Figures 4 and 5).

Development of mountains and fan existence

Rivers with drainage basins larger than 100 km^2 are treated in this chapter, because small rivers without alluvial fans are innumerable. Relationships are presented between the development stage of mountains and the percentage of rivers with alluvial fans in the three regions (Figure 6). The development stage of each range was determined based on Figure 4. In calculating the mean percentage of rivers with fans for each substage, the percentages for each mountain range was weighted by the number of rivers in each range.

The percentage of rivers with alluvial fans in each range shows marked variations, but the mean percentage for each substage indicates a clear trend. The percentage is 0% in the earliest and the early substages, 6% in the younger-middle substage, 23% in the older-middle substage, and 48% in the later substage. The percentage generally increases with the advance in the growing stage of mountains. No alluvial fans have been built around immature mountains of the earliest and the early substages. The slope of the line between the younger-middle substage and the older-middle substage is slightly steeper than the line between the early substage and the younger-middle substage (Figure 6). This fact suggests that the development of alluvial fans is accelerated around mountains in the older-middle substage.

Development of mountains and relief ratios

In rivers with drainage basins greater than 100 km^2 in Japan, Taiwan, and the Philippines, the degree of influence of four important variables on alluvial-fan development can be expressed by the following ratio: $R_d : A_d : T_a : P_r \fallingdotseq 15:8:6:1$, where R_d, A_d, T_a, and P_r are relief ratio, drainage-basin area, mean temperature in August, and total amount of precipitation for four rainy months, respectively (Saito 1997a). If mean temperature in January (T_j) is used instead of August temperature, the ratio becomes $R_d : A_d : T_j : P_r \fallingdotseq 11 : 6 : 3 : 1$ (Saito 1995). These results confirm that relief ratio is more important than mean temperatures in August and in January. The relief ratio is associated with riverbed gradient and gravel size around a valley mouth (Saito 1986b).

The lowest relief ratio in rivers with alluvial fans is 20.3‰ of the Muko River in Japan (Figure 2). The percentage of rivers with alluvial fans among rivers with relief ratios between 20 and 30‰ is only 6%, while the percentage is 19% for relief ratios between 30 and 40‰ (Figure 7). Furthermore, the percentage is around 20% for relief ratios of 30 to 70‰. These

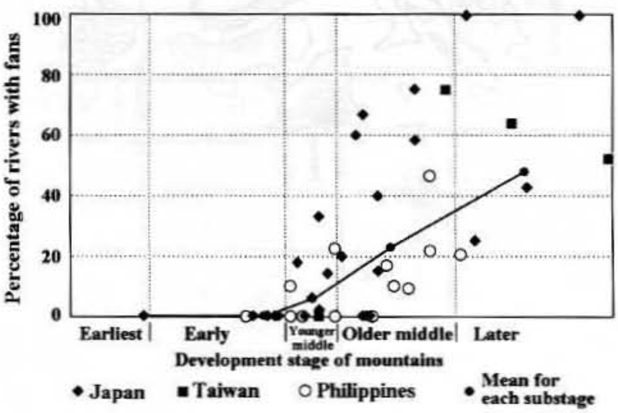

Figure 6. Development substages of mountains and percentages of rivers with alluvial fans. Stages of mountains are based on Ohmori (1978) and Saito (1989, 1997b)

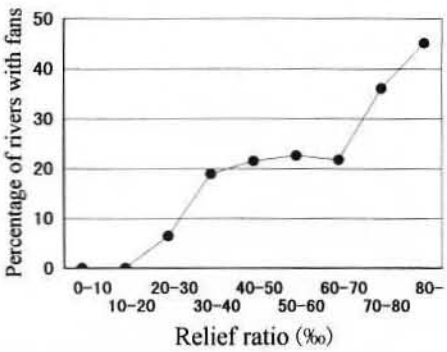

Figure 7. Percentages of rivers with alluvial fans in each rank of relief ratio.

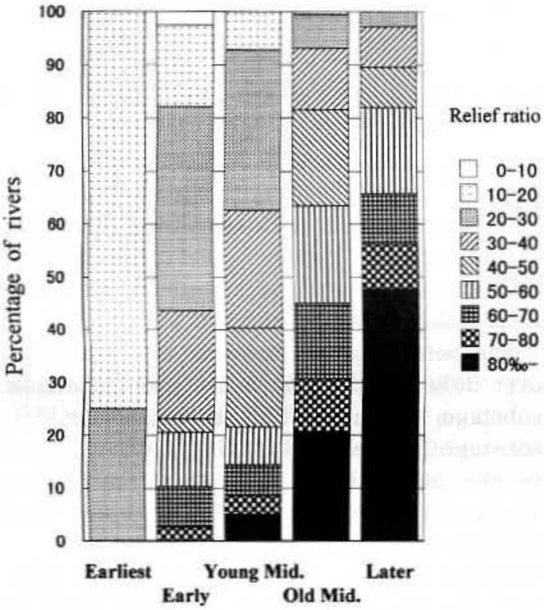

Figure 8. Relief ratios of drainage basins over 100 km² in each substage of mountain development.

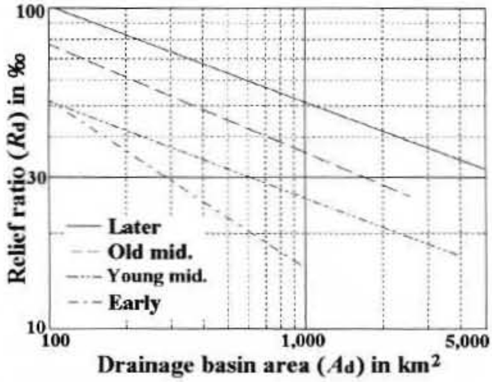

Figure 9. Development substages of mountains and relief ratios.
Early: $R_d=591A_d^{-0.527}$ Younger-middle: $R_d=209A_d^{-0.303}$ Older-middle: $R_d=360A_d^{-0.334}$ Later: $R_d=402A_d^{-0.298}$

facts suggest that the relief ratio of 30‰ is an important threshold for the existence of an alluvial fan.

The percentage of rivers with relief ratios over 30‰ is only 63% in the younger-middle substage, while they are 93% in the older-middle substage and 97% in the later substage (Figure 8). As the relief ratio is related to the drainage-basin area, regression lines between relief ratios and drainage-basin areas are shown for each substage (Figure 9).[1] The regression lines indicate that almost all rivers in the older-middle and the later substages have relief ratios over 30‰ in spite of various drainage-basin areas. The high relief ratio makes alluvial-fan development accelerated in mountains from the older-middle substage.

Development of Mountains and Fan Size

Development of mountains and fan size

Good relationships have been demonstrated between drainage-basin area and alluvial-fan area (Bull 1964). In Japan, drainage-basin area is the most important factor among 13 factors affecting alluvial-fan area (Saito 1985a). Hence, regression lines between drainage-basin area and alluvial-fan area were calculated for each substage of development of mountains in the three regions (Figure 10).[2] Since the size of alluvial fans in deposition areas facing the ocean is comparatively small (Saito 1985b), such fans were not taken for the calculation. There is little difference between the line for the later substage and the line for the older-middle substage. However, there is a significant difference in height between the line for the younger-middle substage and the line for the older-middle substage. This means that an alluvial fan in the older-middle substage is larger than a fan in the younger-middle substage, as indicated by Saito (1986a) for Japanese alluvial fans.

The slopes of the regression lines for the

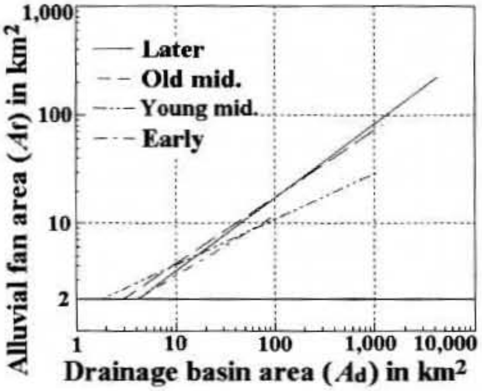

Figure 10. Drainage-basin areas and areas of alluvial fans, except those facing the ocean, in each substage of mountain development.
Early: $A_f=0.911A_d^{0.555}$
Younger-middle: $A_f=1.549A_d^{0.427}$
Older-middle: $A_f=1.015A_d^{0.619}$
Later: $A_f=0.753A_d^{0.681}$

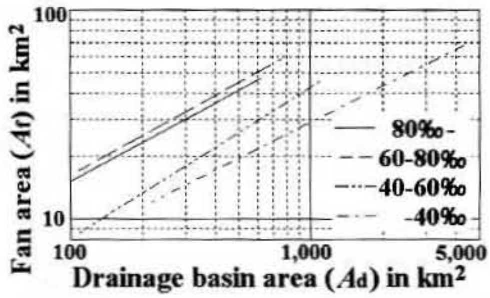

Figure 11. Drainage-basin areas and areas of fans, except those facing the ocean, in each rank of relief ratios.
Lower than 40‰: $A_f=0.555A_d^{0.575}$
Between 40 and 60‰: $A_f=0.290A_d^{0.723}$
Between 60 and 80‰: $A_f=0.899A_d^{0.630}$
Higher than 80‰: $A_f=0.853A_d^{0.625}$

older-middle and the later substages are steeper than those for the early and the younger-middle substages (Figure 10). For a given increase in drainage-basin area on a steeper regression line, the increase of alluvial-fan area is greater. In other words, the influence of a drainage-basin area upon a fan area for the former substages are stronger than that for the latter substages.

Relief ratios and fan size

Alluvial-fan areas are also controlled by the dispersion of altitude in drainage basins (Oguchi and Ohmori 1994). As the dispersion of altitude appears to be correlated with relief ratios, relief ratios seem to affect alluvial-fan areas. However, it is impossible to derive relationships between drainage-basin areas and alluvial-fan areas for small drainage basins with various relief ratios, because small drainage basins with alluvial fans do not have low relief ratios. Thus, regression lines between drainage-basin areas over 100 km^2 and areas of alluvial fans, except those facing the ocean, were examined in each rank of relief ratios (Figure 11).[3] There is no significant difference between the regression line for mountains with relief ratios greater than 80‰ and the line with relief ratios from 60 to 80‰. These lines are markedly higher than the line for mountains with relief ratios between 40 and 60‰. The line for mountains with relief ratios less than 40‰ is the lowest. These facts suggest that alluvial-fan areas become larger with higher relief ratios in rivers whose relief ratios are lower than 60‰, but that the differences of relief ratios bring no differences of alluvial-fan areas in rivers whose relief ratios are higher than 60‰.

The percentage of rivers with relief ratios over 60‰ is only 14% in the younger-middle substage, while it is 45% in the older-middle substage (Figure 8). Alluvial-fan areas are large in the older-middle substage of mountains where more rivers have relief ratios higher than 60‰, as compared with those in the younger-middle substage. These facts show that mountains in the older-middle substage with increased denudation rates provide good conditions for the existence of alluvial fans and for larger alluvial-fan size.

Climatic conditions and fan size

The regression line between drainage-basin areas and alluvial-fan areas of mountains in the later substage is similar to the line for the older-middle substage, and these lines are higher than the lines for the younger-middle and the early substages (Figure 10). Hence, regression lines between drainage-basin areas and areas of alluvial fans, excluding those facing the ocean, were calculated for mountain ranges which are in the older-middle and the later substages in Japan, Taiwan, and the Philippines (Figure 12). The regression line for Taiwan is the highest,

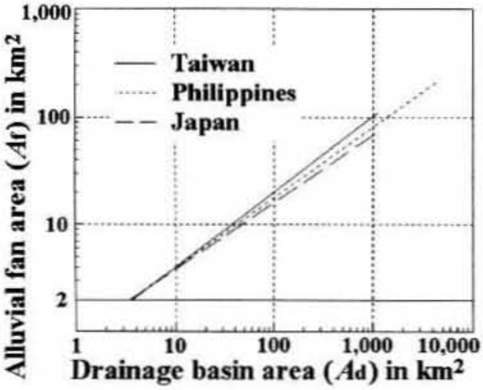

Figure 12. Drainage-basin areas and alluvial-fan areas in Japan, Taiwan, and the Philippines.
Japan: $A_f=0.929A_d^{0.620}$
Taiwan: $A_f=0.807A_d^{0.699}$
Philippines: $A_f=0.891A_d^{0.653}$

but contrary to expectations, the line for the tropical Philippines is not the lowest. In the tropics, it is generally considered that fans should be small due to active fine-sediment production. If this were true, the regression line of the tropical Philippines should be the lowest. However, the line for Japan is the lowest.[4] This indicates that alluvial fans are not smaller in the tropics in spite of the generally unfavorable conditions for their existence. Larger alluvial fans in the Philippines seem to be brought by intense rains or high discharge, as compared with those in northern Japan.

Conclusions

In Japan, Taiwan, and the Philippines, as the development stage of mountains progresses, the relief ratio and the number and size of alluvial fans increase, especially from the older-middle substage of the growing stage. In drainage basins greater than 100 km², the relief ratio of 30‰ is determined to be an important threshold for the existence of an alluvial fan. In the older-middle substage almost all rivers have high relief ratios greater than 30‰, while only 63% of the rivers show such high relief ratios in the younger-middle substage. In addition, the size of alluvial fans in rivers with relief ratios higher than 60‰ is greater than the size with relief rations lower than 60‰. The percentage of rivers with relief ratios over 60‰ in the older-middle substage is markedly higher than that in the younger-middle substage. The increase in rivers with higher relief ratios (or steeper riverbeds), from the older-middle substage provides good conditions for the development of alluvial fans and for larger alluvial fans. Furthermore, the regression line between drainage-basin areas and alluvial-fan areas in the Philippines is not the lowest. This shows that tropical climates do not necessarily produce only small alluvial fans.

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Notes

1. Because only four rivers belong to mountains of the earliest substage, the regression line for the stage is not shown.
2. When a Y-axis value depends on an X-axis value, we use the regression line of Y on X. In this case, as alluvial-fan area depends on drainage-basin area, we should use the line of alluvial-fan area on drainage-basin area. However, the omission of alluvial fans smaller than 2 km² leads to the gentler slope of the line than the slope based on data for all the alluvial fans. In order to estimate an approximate regression line for all fans, two regression lines were calculated. One was a usual regression line of Y on X and another was a regression line of X on Y. I regarded the bisector of these two lines as the best regression line.
3. Since alluvial fans smaller than 2 km² are considered to be few in large drainage basins, a regression line of alluvial-fan area on drainage-basin area was used in this case.
4. Alluvial-fan areas measured on 1 : 50,000 topographic maps could be smaller than those measured on 1 : 25,000 maps. If measurement is carried out on 1 : 25,000 maps in Taiwan and the Philippines, their regression lines would move higher, but the Japanese line would remain the lowest.

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