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Altitudinal Changes in Slope Angle and Profile Curvature in the Japan Alps: A Hypothesis regarding Characteristic Slope Form

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Abstract: Previous research indicated that the average slope angle in Japanese mountains tends to increase with increasing altitude. This paper examines the details of the change for the three ranges of the Japan Alps using 2.25"×1.5" DEMs provided by the Geographical Survey Institute of Japan. Altitudinal changes in profile curvature were also analyzed. The results indicate that the ranges can be divided into three altitude zones. Zone 1 (< ca. 1,000 m) is characterized by an increase in mean and modal slope angle with altitude as well as concave slope profiles. Zone 2 (ca 1,000 to 2,800 m), which occupies the broadest area of the ranges, is characterized by an increase in mean slope angle with increasing altitude, but modal slope angle is around 35 degrees regardless of altitude. The modal profile curvature is also stable around null throughout the zone, reflecting straight slope profiles. The frequency distributions of angle and curvature indicate that the ratio of hillslopes with an angle of ca. 35 degrees to all hillslopes increases with increasing altitude. This finding suggests that hillslopes converge into a characteristic form after long-term erosion. Zone 3 occurs in narrow zones near mountain summits (> ca. 2,800 m) subjected to periglacial actions, wind erosion and Pleistocene glacial erosion. This zone is characterized by decreasing slope inclination with altitude and convex slope profiles.

Key words: morphometry, DEM, slope angle, curvature, the Japan Alps

Introduction

The variation of morphometric parameters within a mountain range has attracted the attention of geomorphologists. For example, Burbank (1992) and Brozovic et al. (1997) examined the differences in slope angle within different altitude zones of the Himalayas, and Kirkbride and Matthews (1997) investigated the morphometric characteristics of the Ben Ohau Range in New Zealand in relation to past changes in snow lines. These researchers used digital elevation models (DEMs) or vectorized contours to compute morphometric parameters such as slope angle.

In Japan, Suga (1985) calculated the morphometric parameters of the Shikoku Mountains using 11.25"×7.5" DEMs, and discussed their relation with geology. Ohmori (1987) investigated the distribution of relief within ranges in central Japan using 1-minute DEMs, and suggested that local relief tends to increase with increasing altitude. Similar altitudinal changes in local relief or slope angle have been deduced by Oguchi (1988a). However, the detailed distribution of morphometric parameters within Japanese ranges has not been fully examined.

The recent CD-ROM release of "50-m DEMs" (with grid intervals of 2.25" in longitude and 1.5" in latitude) by the Geographical Survey Institute of Japan permits the intensive morphometric analyses of Japanese mountain ranges. These DEMs are considered to have appropriate resolution for calculating the angle and curvature of rugged Japanese mountains (Nogami, 1995). Using the new DEMs, this paper discusses the details of altitudinal changes in morphometric variables within the Japan Alps, the highest non-volcanic ranges in Japan. Slope angle and profile curvature were selected as the basic morphometric parameters to be examined. Data were arranged and analyzed with the aid of Geographical Information Systems (GIS).

Study Area and Methods

The mountain ranges investigated are the Northern, Central, and Southern Japan Alps (Figure 1) in Central Japan. They have an area between ca. 1400 to 5400 km2 and a relief of ca. 2,700 to 3,200 m (Table 1). These three ranges are characterized by different geological settings. Sedimentary rocks widely occur in the Southern Japan Alps; whereas, granitic rocks occur in most of the Central Japan Alps. The Northern Japan Alps consist of both sedimentary and granitic rocks.

Recent research suggested that the ranges have different orogenic histories. The Northern Japan Alps were uplifted to form a large-relief range by the end of the Tertiary, the Southern Japan Alps began uplifting in the early Quaternary, and the Central Japan Alps are the youngest ranges having started uplifting about 0.5 Ma (Ikeda, 1990; Moriyama, 1990).

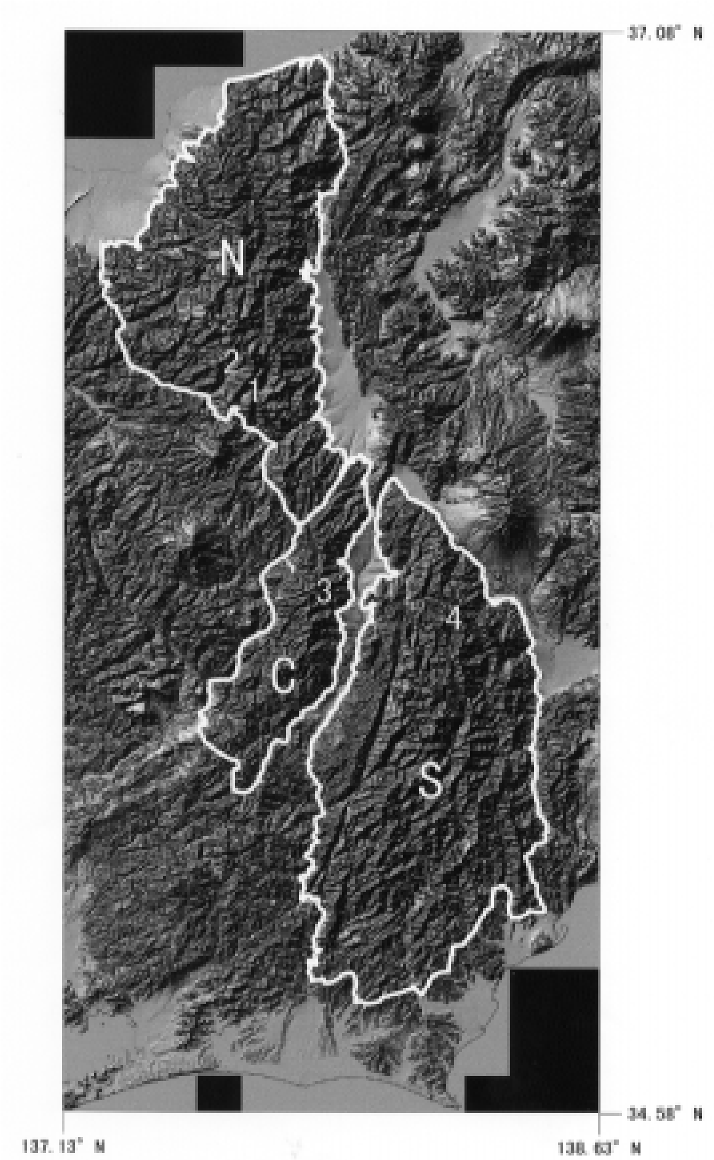

Figure 1. Shaded relief image of the study area showing the location of the three ranges. (Source: 2.25"×1.5" DEMs, the Geographical Survey Institute of Japan)

N: Northern Japan Alps, C: Central Japan Alps, S: Southern Japan Alps. White lines show mountain boundaries.

1: Kamikochi Valley, 2-4: three sites where the data in Figure 8 were sampled (2: Mt. Kasa, 3: Mt. Kisokoma, 4: Mt. Senjyo).

Area	Aluititude (m)				Area (km^2)	Grid Spacing (m)	
	Min	Max	Mean	Standard Dev.		X	Y
Northern Japan Alps	0	3190	1313.9	643.2	4067.3	56.1	46.2
Central Japan Alps	265	2956	1272.6	457.2	1464.0	56.6	46.2
Southern Japan Alps	35	3192	1089.6	593.3	5397.4	56.8	46.2

Table 1. Basic topographic properties and grid spacing of DEMs for the three ranges.

Digital elevation data for the three ranges were compiled from the 2.25"×1.5" DEMs. The DEMs supplied by the CD-ROMs consist of electronic files each of which has an area of 7'30" in longitude by 5' in latitude. Files including at least a part of each range were combined into one mosaic file for each range. Then data outside of the range were blanked using the digitized vector data of mountain outlines (Figure 1). Most of the mountain outlines correspond to boundaries between mountain slopes composed of consolidated bedrock and piedmont depositional surfaces such as alluvial fans. In areas where the mountain range is bordered by hilly lands; however, the outlines correspond to major valleys between the range and hills.

The DEMs contain altitude data for the water surface of major lakes. Fifteen large lakes associated with artificial dams are located within the ranges. The data for the lakes are blanked using the vector data of lake outlines. Although almost all the three ranges consist of steep hillslopes, there is a flat and wide depositional surface in and around Kamikochi in the Northern Japan Alps (1 in Figure1). This surface was created by the damming of the Azusa River due to volcanic activities. The height data for the flat surface were also blanked.

The metric distance between the grid points of the DEMs changes with changing latitude or longitude. Within each range, however, the change in distance is very small and can be assumed to be negligible. Therefore, the metric grid interval at the center of each range was used in calculating the morphometric parameters from the DEMs (Table 1).

Three basic topographic parameters are analyzed in this paper: altitude, slope angle, and profile curvature. Angle and profile curvature were selected because the former is directly related to the mobility of slope material, and the latter is related to the type of slope processes (e.g., Kirkby, 1971). The calculation of angle and curvature were performed using the central difference between four neighboring points at a grid point on the DEMs. The algorithm for the calculation is based on Dozier and Strahler (1983), Mitasova and Hofierka (1993) and Keckler (1995). The calculated angle and curvature were saved as grid data along with altitude data. Then the grid data were imported into ArcView, a GIS software package from ESRI (Redlands, USA), for performing the analysis.

Results

Altitudinal change in slope angle

The frequency distribution of slope angle for different altitude zones was investigated to discuss general changes in hillslope angles with altitude (Figures 2 to 4). The altitude zones or bins were divided into 0 to 499 m, 500 to 999 m, 1,000 to 1,499 m, 1,500 to 1,999 m, 2,000 to 2,499 m, and 2,500 to 2,999 m. The total area of each bin was normalized to compare the data for different bins with different areas. The analytical results revealed that the altitudinal change in the frequency distribution of slope angle is very similar among the three ranges. With increasing altitude, gentle slopes tend to diminish and slopes with an angle of around 35 degrees increase.

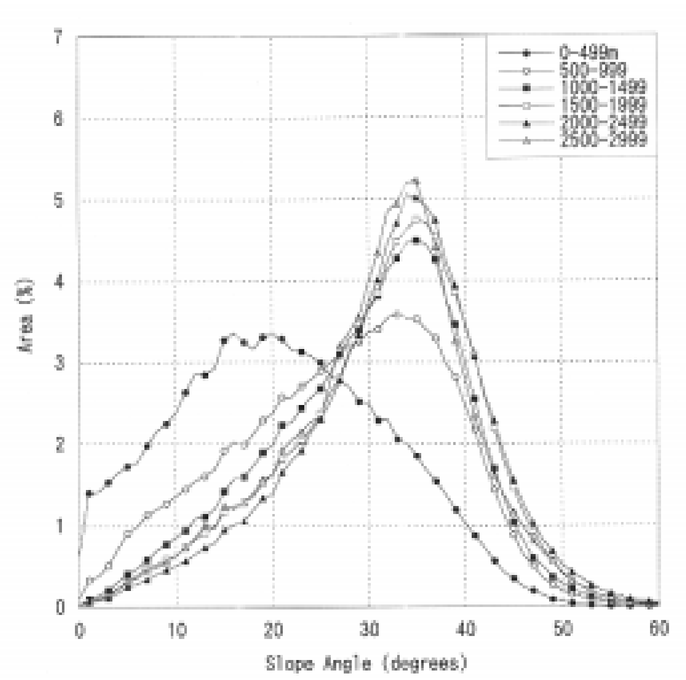

Figure 2. Altitudinal change in frequency distributions of slope angle for the Northern Japan Alps. Data were arranged using 500 m altitude bins.

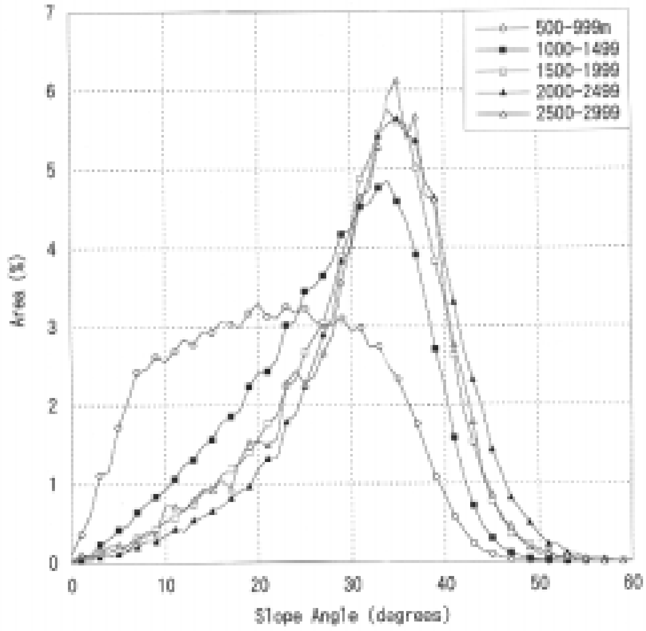

Figure 3. Altitudinal change in frequency distributions of slope angle for the Central Japan Alps. Data were arranged using 500 m altitude bins.

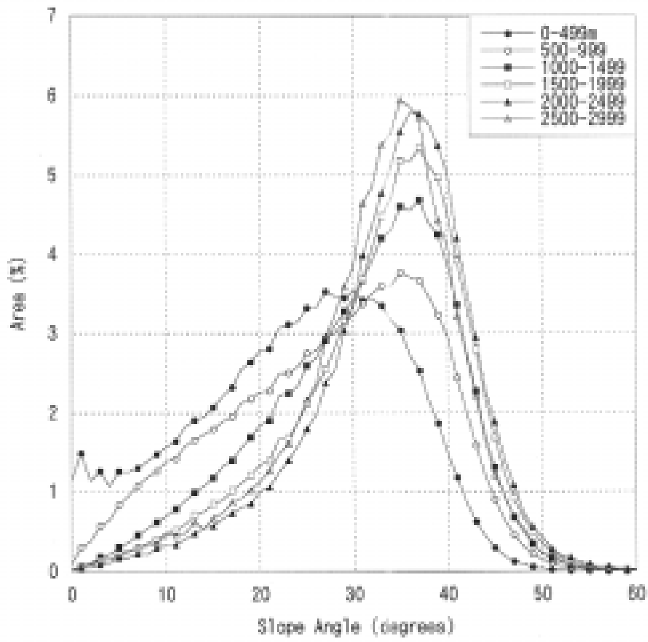

Figure 4. Altitudinal change in frequency distributions of slope angle for the Southern Japan Alps. Date were arranged using 500 m altitude bins.

More detailed altitudinal change in slope angle was investigated using data for 50-m altitude bins. Figures 5 to 7 show mean slope angle, modal slope angle and the standard deviation of slope angle for each bin. Mean angle tends to increase with increasing altitude below ca. 2,200 m. For higher altitudes, mean angle generally decreases with altitude except for the altitude zone around 3,000 m in the Northern Japan Alps. Despite the change in mean slope angle, modal angle tends to be constant around 35 degrees for altitudes between ca. 1,000 to 2,800 m. The standard deviation of slope angle is relatively large for altitudes less than 1,000 m and more than 2,800 m. For altitudes between 1,000 to 2,800 m, the standard deviation generally decreases with increasing altitude meaning that more hillslopes have an angle of around 35 degrees at higher altitudes.

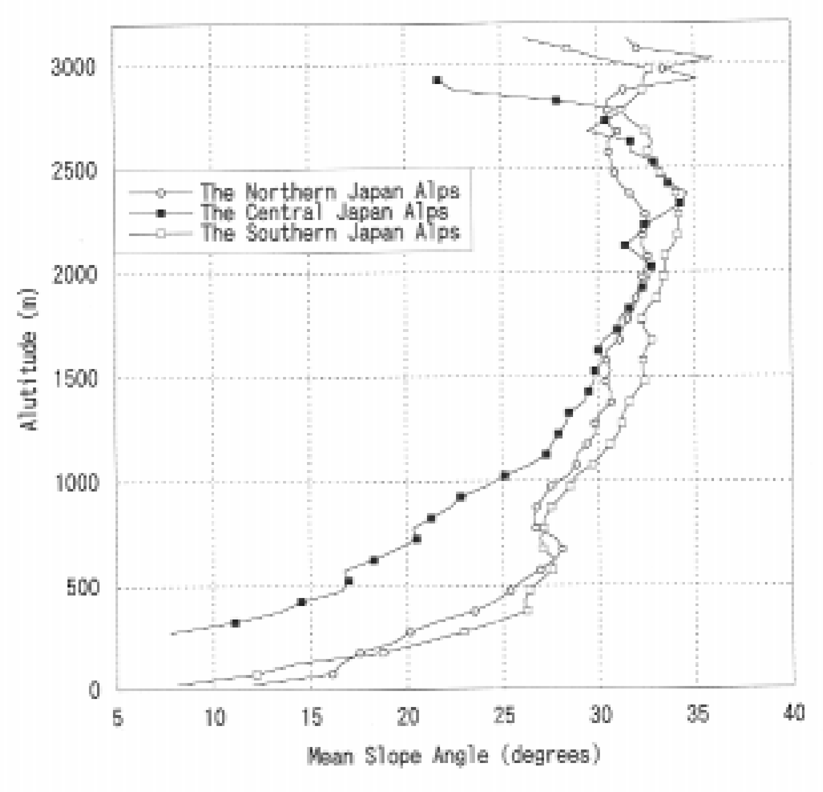

Figure 5. Altitudinal change in mean slope angle.

Data were arranged using 50 m altitude bins.

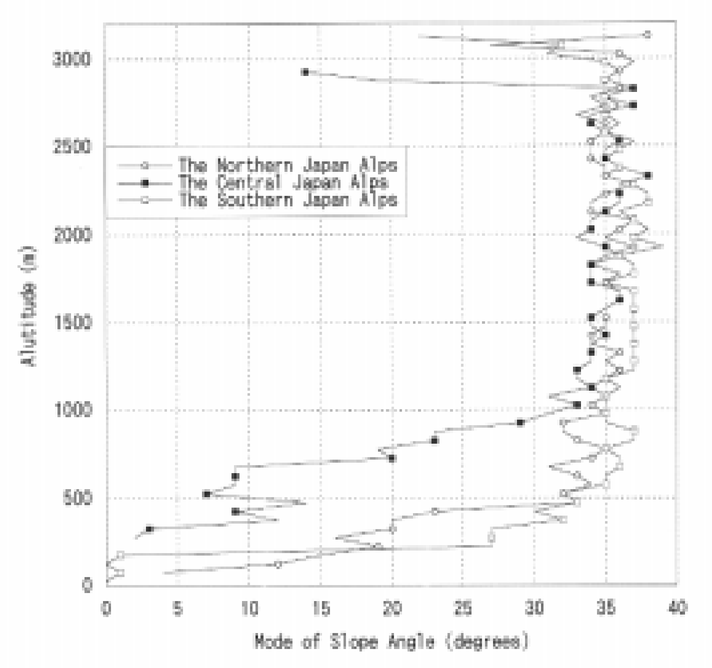

Figure 6. Altitudinal change in mode of slope angle.

Data were arranged using 50 m altitude bins.

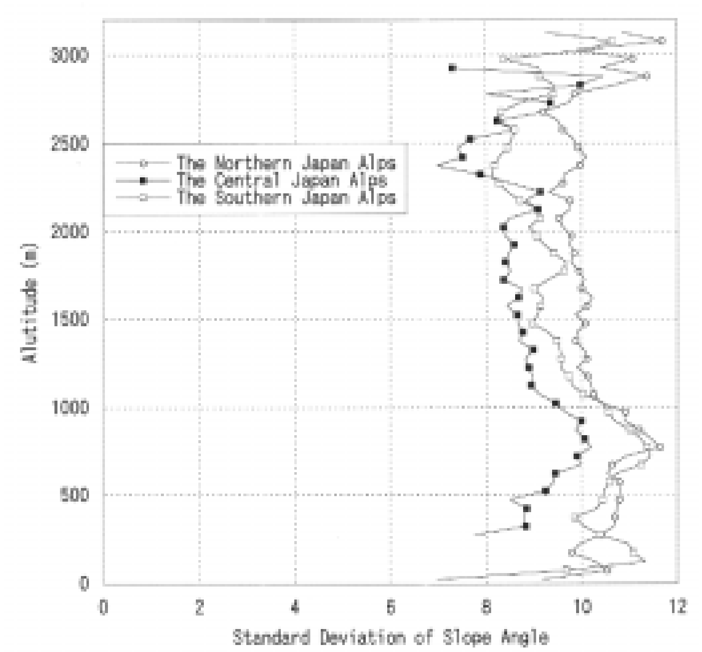

Figure 7. Altitudinal change in standard deviation of slope angle.

Data were arranged using 50 m altitude bins.

Various methods have been proposed to calculate slope angle from DEMs (e.g., Sharpnack and Akin, 1969; Evans 1980; Papo and Gelbman, 1984; Mitasova and Hofierka, 1993). The applicability of the method used in this study was evaluated using data for three sample areas. Each area has a size of 22.5" in longitude and 15" in latitude containing 100 grid points from the DEMs. The areas were selected from three ranges: near Mt. Kasa in the Northern Japan Alps, near Mt. Kisokoma in the Central Alps and near Senjyo in the Southern Alps (2, 3 and 4 in Figure 1, respectively). The areas have altitudes between 1,600 to 2,500 m, which fall into the altitudinal range where modal slope angle is almost constant around 35 degrees. Using the enlargements of 1: 25,000 topographic maps provided by the Geographical Survey Institute of Japan, slope angle for each 2.25"×1.5" cell was estimated using the contour counting method developed by Horton (1932). The estimated angle was plotted against the DEM-derived slope angle (Figure 8). The result shows that slope angles calculated by the two methods are mostly in agreement[1]. For example, the cells with ca. 35 degrees of DEM-derived angle have ca. 28 to 42 degrees of map-derived angles. In other words, the DEM-derived slope angle reflects the actual slope angle, especially for angles of around 35 degrees.

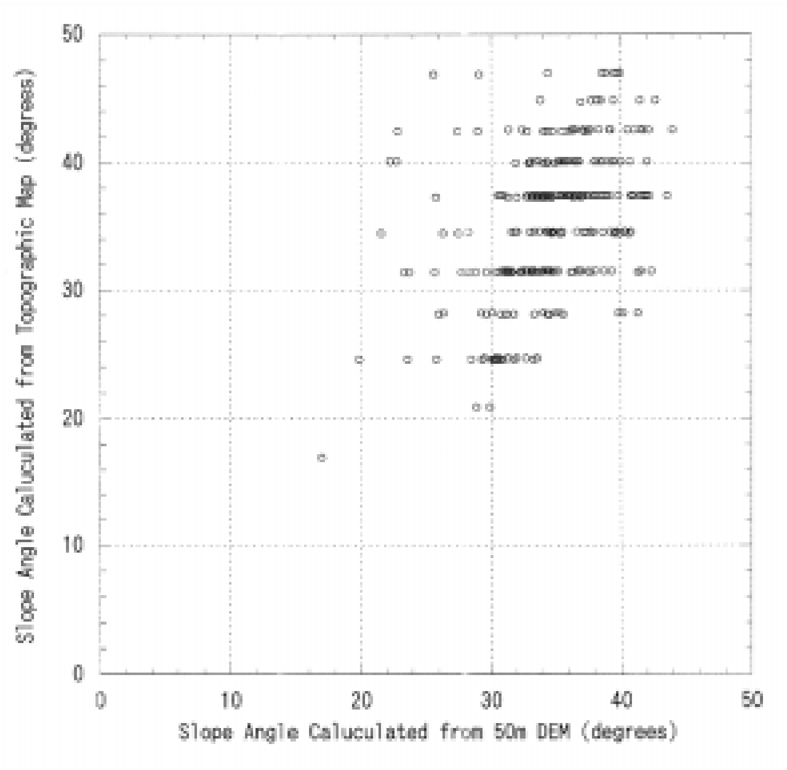

Figure 8. Relationship between slope angles calculated from 1/25,0000 topographic maps and those from 2.25"×1.5" DEMs.

Altitudinal change in profile curvature

The frequency distribution of profile curvature for each of the 500-m altitude bins was examined (Figures 9 to 11). The three ranges have similar characteristics, in that the ratio of hillslopes with curvature around zero increases with altitude in all bins except the highest bin. The modal curvature is zero for all altitude bins indicating the dominance of straight slope profiles.

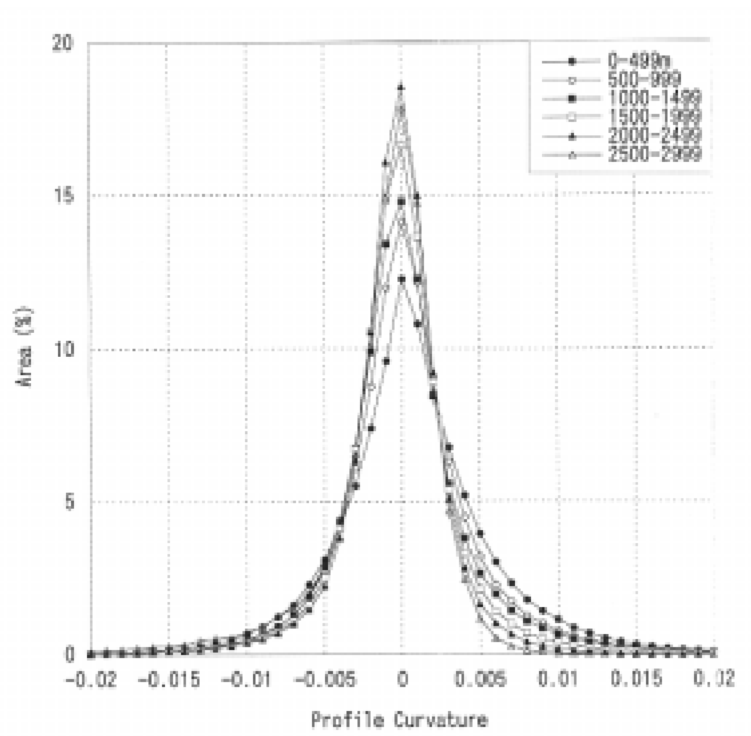

Figure 9. Altitudinal change in frequency distributions of profile curvature for the Northern Japan Alps.

Data were arranged using 500 m altitude bins.

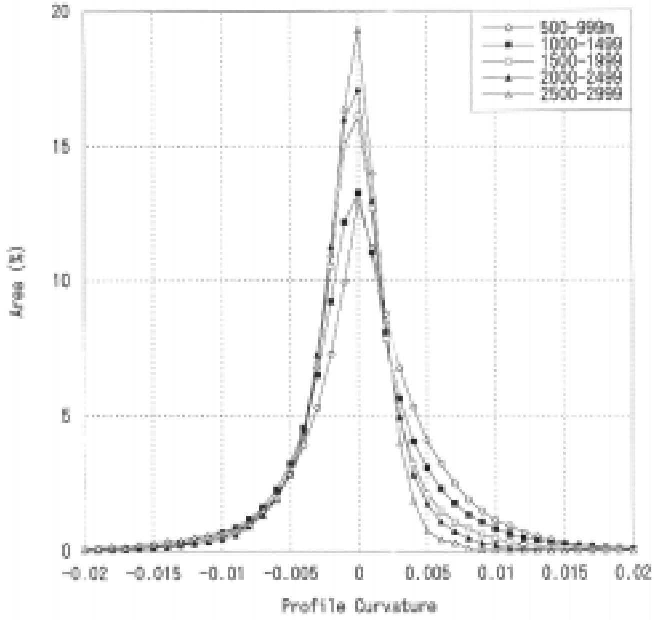

Figure 10. Altitudinal change in frequency distributions of profile curvature for the Central Japan Alps.

Data were arranged using 500 m altitude bins.

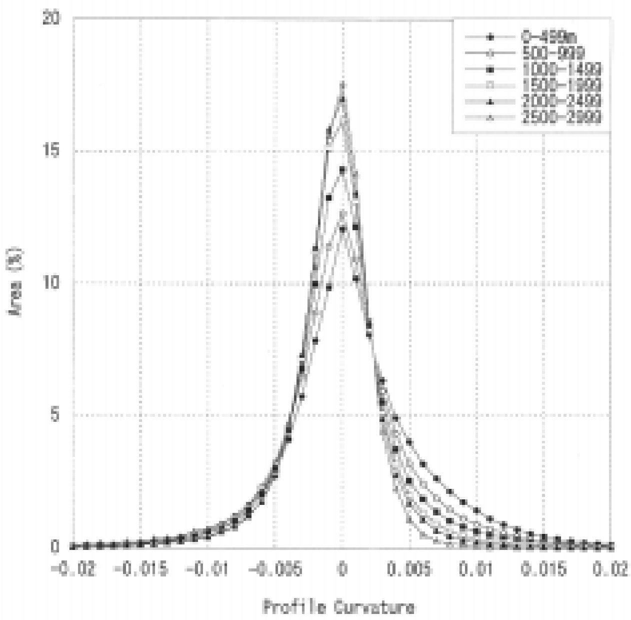

Figure 11. Altitudinal change in frequency distributions of profile curvature for the Southern Japan Alps.

Data were arranged using 500 m altitude bins.

The mean and standard deviation of profile curvature for each of the 50-m altitude bins were also calculated (Figures 12 to 13). The mean curvature generally decreases with altitude for all the ranges despite the fact that the modal curvature is stable around zero. This observation indicates that concave hillslopes occur more frequently at lower altitudes. The change in concavity, however, is not significant for altitudes between ca. 500 to 2,300 m where mean curvature is around zero. For these altitudes, the standard deviation consistently decreases with increasing altitude, meaning that more hillslopes have nearly straight form at higher elevations.

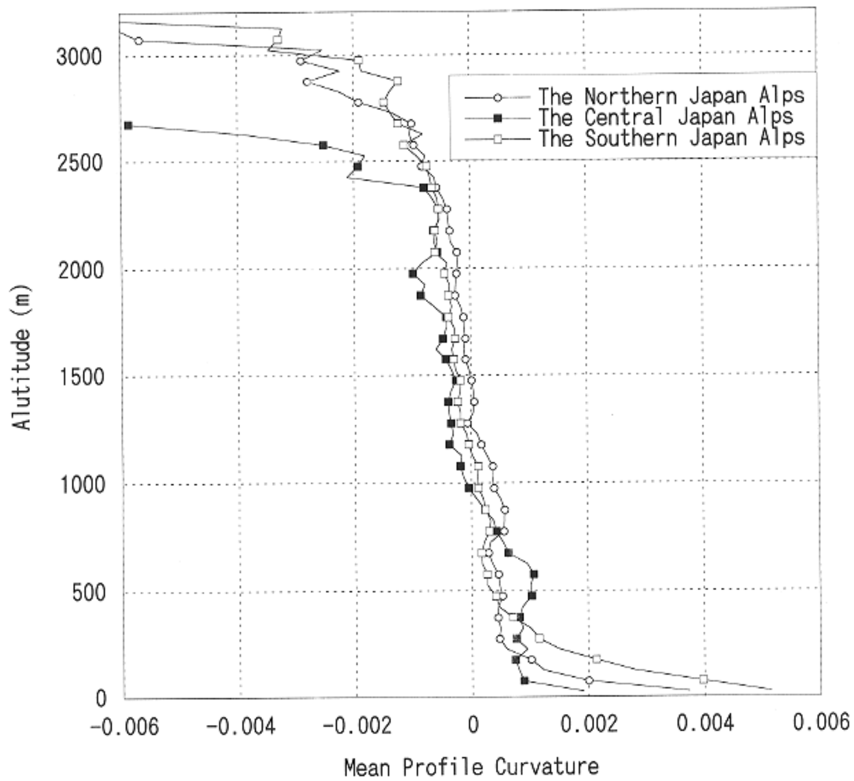

Figure 12. Altitudinal change in mean profile curvature.
Data were arranged using 50 m altitude bins.

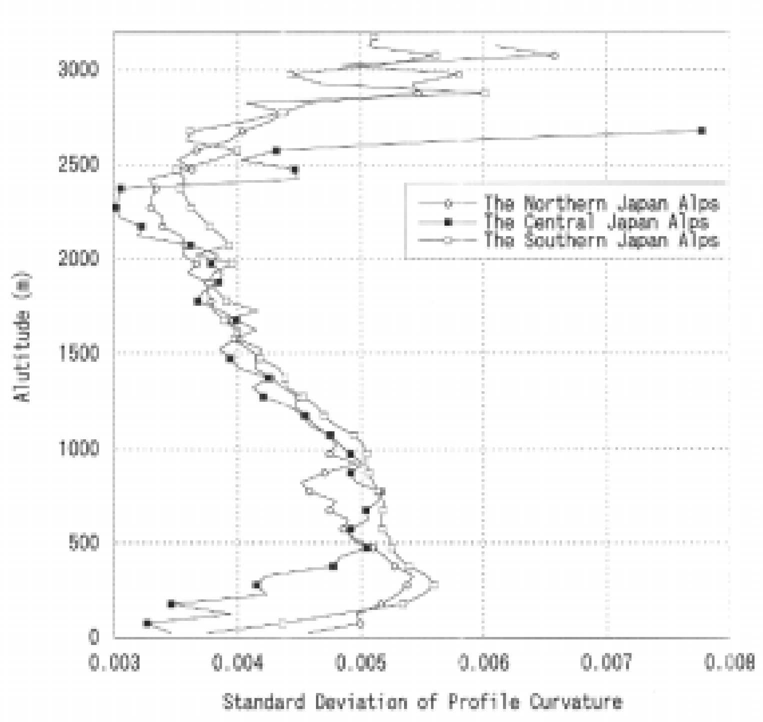

Figure 13. Altitudinal change in standard deviation of profile curvature.
Data were arranged using 50 m altitude bins.

Relationship between slope angle and profile curvature

The mean and standard deviation of profile curvature were calculated for each 1-degree bin of slope angle. Figure 14 shows the relationship between the calculated mean profile curvature and the slope angle. Data for mean slope angles greater than 55 degrees are not shown because of the very small number of data points. The figure shows that the mean profile curvature for lower slope angle is positive, but it is almost null or slightly negative for slope angles of more than 30 degrees. Figure 15 shows the relationship between the standard deviation of profile curvature and slope angle. The standard deviation is large for lower slope angles around ten degrees pointing to large variety in slope concavity. In contrast, the deviation is small and nearly constant for slope angles of more than 35 degrees. It can be said that hillslopes with an angle of more than 35 degrees mainly have a straight form.

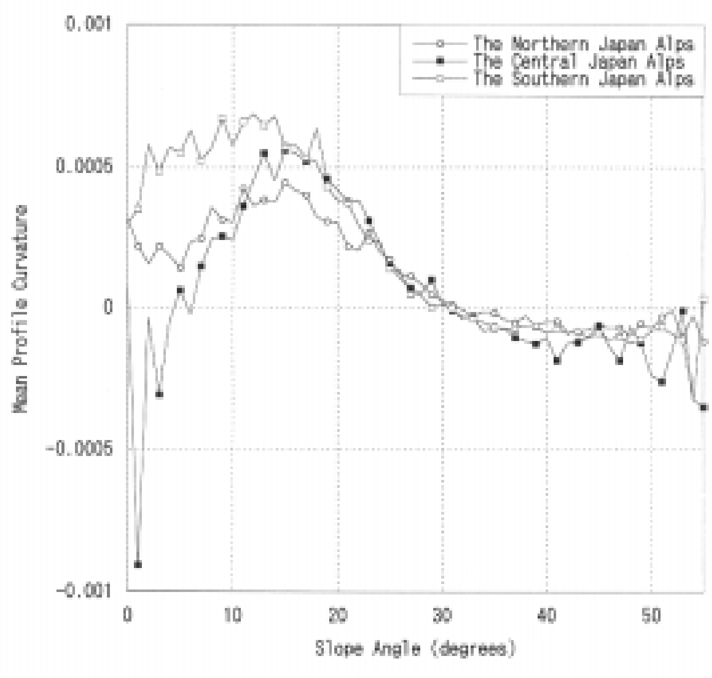

Figure 14. Relationship between slope angle and mean profile curvature.

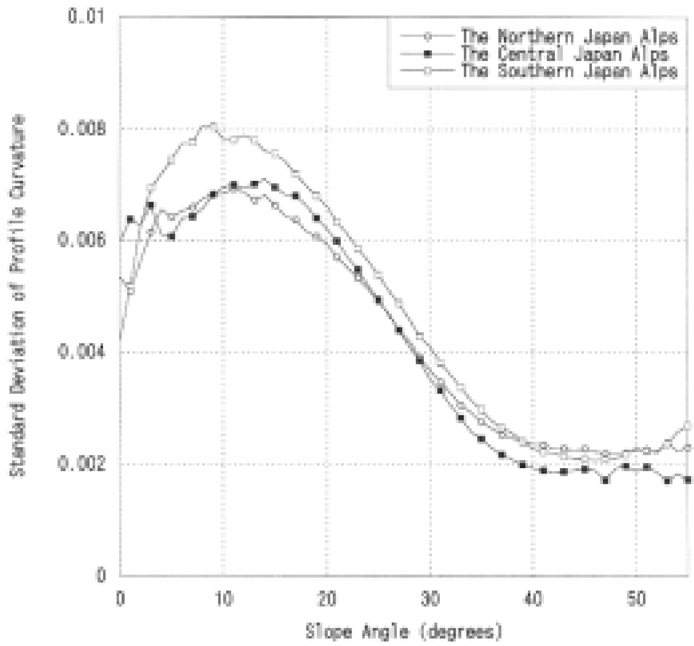

Figure 15. Relationship between slope angle and standard deviation of profile curvature.

Discussion

The relations among altitude, slope angle and profile curvature indicate that the ranges of the Japan Alps can be divided into three geomorphological zones: Zone 1 (< ca. 1,000 m in altitude), Zone 2 (ca 1,000 to 2,800 m) and Zone 3 (> ca. 2,800 m). In Zone 1, both mean and modal slope angles increase with altitude. The majority of hillslopes have concave profiles but the variety of concavity is large. In Zone 2, mean slope angle increases with increasing altitude, but modal slope angle is around 35 degrees regardless of altitude. The modal profile curvature is around zero throughout the zone. The ratio of hillslopes with an angle of ca. 35 degrees to all hillslopes increases with altitude. In Zone 3, slope inclination decreases with increasing altitude. Hillslopes tend to have convex profiles.

The changes in morphometric parameters in Zone 2 are the most important because the zone occupies the largest part of the ranges. Within the zone, hillslopes tend to converge into a straight form with an angle of ca. 35 degrees, particularly at higher altitudes subjected to intensive erosion. Erosional processes in Zone 2 are mostly fluvial valley incision and mass wasting such as slope failure. It can be assumed that these processes ultimately create a characteristic type of hillslopes with an angle of ca. 35 degrees.

There are two hypotheses for the formation of the characteristic hillslopes. The first one is associated with the fact that the angle of repose for clastic slope materials is ca. 35 degrees. Takeshita (1985) suggested that the accumulation of clastic materials creates talus slopes with an angle of ca. 35 degrees in Japanese ranges. In the Japan Alps, however, the distribution of talus slopes with thick deposits is confined to limited areas. The majority of hillslopes in Zones 2 and 3 are covered only with thin regolith reflecting rapid erosion by slope failure and gullying (e.g., Oguchi, 1988b, 1996). Therefore, the effects of the angle of repose on depositional processes probably play only a minor role in determining hillslope angle in the Japan Alps.

The second hypothesis is related to erosion rather than deposition. It can be assumed that the angle of mountain slopes under rapid uplift tends to increase with the progress of valley erosion. However, if hillslopes of more than 35 degrees are highly unstable and easily eroded, more hillslopes should have an angle of about 35 degrees with the progress of erosion. This hypothesis agrees with the observed fact that hillslopes more than 35 degrees have a much higher frequency of shallow slope failure than gentler hillslopes (Yanai, 1989; Iida, 1999). In steep Japanese ranges, such as the Japan Alps, not only shallow failures but also erosion into bedrock such as gullying and deep landsliding play significant roles in shaping landscapes (e.g., Sugai, 1990; Oguchi, 1996). This fact suggests that hillslopes of more than 35 degrees tend to be eroded rapidly not only by shallow failure, but also by bedrock erosion. Burbank et al. (1996) also inferred that bedrock erosion is responsible for determining the most dominant hillslope angle in the northwestern Himalayas.

Although the three ranges have different geology, altitudinal changes in slope angle and profile curvature are basically common to all the ranges indicating that geology has played a limited role in shaping the general forms of the ranges. Oguchi (1997a) also indicated that the frequency of the major ridges and ravines in the Northern Japan Alps does not change significantly according to geology. The effect of geology on mountain slopes may be more marked for smaller-scale landscapes, such as the form of channel walls and the extent of post-glacial erosion (Oguchi, 1988a, 1996, 1997a; Onda, 1994).

Smaller hillslope angle in Zone 1 points to smaller valley incision in and around piedmont areas. Larger mean slope concavity in the zone may reflect the occurrence of concave colluvial slopes at the mountain foot. In contrast, smaller slope angle and large convexity in Zone 3 probably reflects strong erosion due to periglacial processes, wind action and Pleistocene glacial erosion (Oguchi, 1997b). Convex hillslopes near the top of the Japan Alps have been ascribed to soil creep associate with periglacial actions (Sugai, 1990, 1992). Steeper slopes at altitudes of around 3,000 m in the Northern Japan Alps correspond to large cirque walls around Mt. Hotaka.

To summarize, fluvial erosion and mass movement have eroded the three ranges of the Japan Alps to form characteristic hillslopes with an angle of ca. 35 degrees, except in the lowest and highest parts of the ranges. Hillslopes of more than 35 degrees in angle cannot survive for a long time because of rapid erosion.

The difference in orogenic history among the three ranges appears to be unrelated to the general trend of altitudinal changes in morphometric parameters. The younger orogeny of the Central Japan Alps, however, may have led to minor geomorphological differences from the other two ranges. For example, slope angle for the altitude zone between 500 to 999m in the Central Japan Alps is smaller than that of the other ranges (Figures 2 to 4). This fact may reflect a lesser amount of total valley incision in the lower part of the younger Central Japan Alps (Ikeda, 1990). Such geomorphological differences between Japanese ranges need to be investigated in the future.

Acknowledgements

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Note

1. The ratio of map-derived slope angle to DEM-derived angle in Figure 8 falls in a range between 2/3 and 3/2, except several points having a ratio more than 3/2. These points correspond to very narrow ridges and valleys that cannot be detected by the DEMs. The existence of such landforms does not affect the analysis of

general morphometric characteristics because they occupy only small areas.

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