Classification and formation environment of glacial valleys based on morphometric analyses

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Abstract—**This paper analyzes glacial valleys in the Swiss Alps, the Himalayan Range, Yosemite, the New Zealand Southern Alps, and Patagonia using DEMs. Transverse and longitudinal profiles of four to six valleys in each region were obtained and the aspect/form ratio (*FR*) and slope of each small segment of a transverse profile were calculated. Forms of glacial valleys were evaluated using *FR* and the kurtosis, skewness, and standard deviation of slope. *FR* tends to converge into 0.28 with increasing valley size, which may correspond to the balance of vertical and lateral glacial erosion as well as a threshold slope angle for slope failure after deglaciation. The transverse profiles were classified into four types based on their geomorphometric properties: 1) U-shaped, 2) V-shaped, 3) plain, and 4) others. The most common type, other than "others" that include various forms, is U-shaped in New Zealand and Patagonia, V-shaped in the Himalayas, and plain in Yosemite and the Swiss Alps. These differences may reflect regional characteristics of snowfall, mass wasting, tectonics, and the history of glacier advances. *FR* may also indicate the past location of the glacial equilibrium line.**

INTRODUCTION

Glacial valleys or troughs are a major type of glacial landforms, and their transverse sections are widely known as U-shaped [1]. Although some researchers investigated the form of transverse profiles of glacial valleys, they typically focus on theoretical interpretation of U-shaped form [2, 3] or net volume of erosion [4]. Detailed studies on the actual shape of glacial valleys, including discussion on whether they are really U-shaped, have been limited to a few case studies [5, 6]. The objectives of this paper are: 1) to analyze the detailed morphometric characteristics of glacial valleys in various regions of the world using digital elevation models (DEMs); 2) to classify glacial valleys based on the statistical analysis of the shape of transverse profiles; and 3) to discuss environmental factors affecting glacial-valley forms.

STUDY AREAS AND METHODS

The study areas are typical glaciated mountains in the Swiss Alps, the Himalayan Range, Yosemite, the New Zealand Southern Alps, and Patagonia. Four to six deep and wide glacial valleys without large existing glaciers were selected from each area for detailed morphometric analysis. Valleys that underwent glaciation during MIS2 (Last Glacial Maximum) were selected to minimize the effect of postglacial erosion. The names of the selected valleys are shown in Table I. Fig. 1 shows maps illustrating the distribution of the four glacial valleys in Patagonia, adjacent to the Hielo Patagonico Norte Icefield. Like this case, the selected valleys tend to be located near large existing glaciers.

TABLE I. SELECTED GLACIAL VALLEYS.

Area	Valleys
Swiss Alps	Burgli, Heimritz, Kandersteg, Lauterbrunnen, Leukerbad, Schwanden
Himalaya	Lachung, Mangan, Pandim, Sikkim
Yosemite	Long Mountain, Lyell A, Lyell B, Lyell C, Tower, Yosemite
NZ Southern Alps	Dechen, Fettes, Fiordland, Manapouri, Sefton
Patagonia	San Rafael, San Valentin, Teresa, Tortel

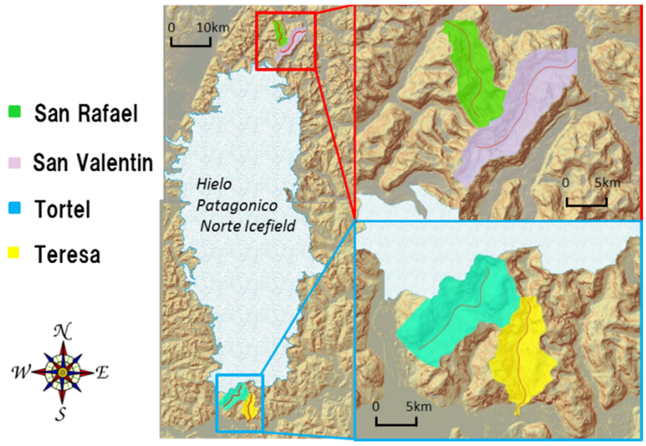

Figure 1. Maps showing the location of the four selected glacial valleys in Patagonia.

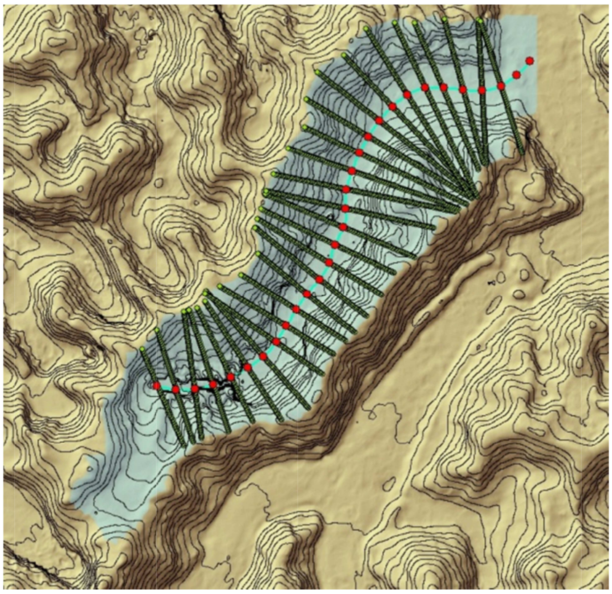

Figure 2. Morphometric measurements of the San Valentin glacial valley in Patagonia. Red points show the bottom of the valley (1 km interval). Green lines through the points show the location of obtained transverse profiles.

Longitudinal and transverse profiles of each glacial valley were obtained from the ASTER-G DEM, based on the method of Lin and Oguchi [7] (Fig. 2). Although the accuracy of the DEM is limited, it allows us to analyze the general characteristics of large and deep valleys like those we studied. Both ends of a transverse profile basically follow the drainage divide as shown in Fig. 2. However, if there is a marked break of slope below the divide, the break is used as the end. If significant topographic modification such as the entrance of a tributary is observed along a transverse profile, the profile is not used for further analysis.

We computed the aspect/form ratio (*FR*; total height/total width [4]) of each transverse profile and slope of each small segment of the profile (30 m interval in horizontal length). From the frequency distribution of the slope values, statistical moments including kurtosis (*Kr*), skewness (*Sk*), and standard deviation (*Sd*) were computed for each profile. Because of large valley sizes and the 30-m sampling interval, the number of data for each profile was sufficient for computing the statistical moments. Forms of glacial valleys were evaluated using these moments as well as *FR*. We did not deal with areas covered with existing glaciers. As noted, the selected valleys do not contain any large glaciers.

RESULTS AND DISCUSSION

Correlations between any two of the four parameters (*FR*, *Kr*, *Sd* and *Sk*) were investigated. Considering the correlations and observing the actual form of the transverse sections, we classified the sections into four types according to the combinations of the parameter values: 1) U-shaped, 2) V-shaped, 3) plain (valley width is much larger than depth), and 4) others (Table II). The "large" and "small" parameter values in Table II correspond to upper and lower 30% values of each parameter, respectively, as illustrated in Fig. 3. One valley often meets more than one conditions shown in Table II. In such a case, the type with the largest number of conditions met is regarded as the type of the valley. If none of the conditions in Table II is met, the type of the valley is "others". In addition, if two types share the same largest number of conditions met, the type of the valley is also "others". Fig. 4 shows typical examples of the U-shaped, V-shaped and plain types.

TABLE II. TYPES OF TRANSVERSE SECTIONS AND CORRESPONDING COMBINATIONS OF PARAMETERS.

U-shaped	**V-shaped**	**Plain**
large *FR*, small *Kr*	large *FR*, large *Kr*	small *FR*, large *Kr*
large *FR*, large *Sk*	large *FR*, small *Sd*	small *FR*, large *Sk*
large *FR*, large *Sd*	large *Kr*, small *Sd*	small *FR*, small *Sd*
small *Sk*, large *Sd*	large *Kr*, small *Sk*	large *Kr*, large *Sk*
	small *Sk*, small *Sd*	large *Sk*, small *Sd*

FR: form ratio, *Kr*: kurtosis of slope, *Sd*: standard deviation of slope, *Sk*: skewness of slope. large = values belonging to upper 30% of the total population. small = values belonging to lower 30%.

The classification results for all transverse profiles in the five regions revealed that the most common valley-form type other than "others", is U-shaped in New Zealand and Patagonia, V-shaped in the Himalayas, and plain in Yosemite and the Swiss Alps (Table III). These observations may be interpreted as follows. In New Zealand, highly abundant snowfall let glaciers create typical U-shaped valleys. In the Himalayas both V-shaped and U-shaped valleys are abundant and they have high *FR* values, indicating that active glacial erosion, mass movements after deglaciation, and rapid tectonic uplift contributed to valley formation. The high proportion of the plain type in Yosemite and the Swiss Alps may reflect smaller precipitation in both regions, a low uplift rate in Yosemite, and marked glacial re-advances in the Swiss Alps that led to stepped valley-side slopes. *FR* of valleys in Patagonia tends to be small because of active lateral erosion by ice sheets; therefore U-shaped valleys there differ from those in the Himalayas and can be referred to as elongated box-shaped. The above discussion indicates that glacial valleys are not necessarily U-shaped, and the variety of their forms is due to the regional characteristics of precipitation, tectonics, glaciation histories, and post-glacial erosion. Therefore, it is important to examine the shape of valleys in relation to the effects of various factors even in glaciated areas [4].

As a common trend for all glacial valleys investigated, *FR* tends to converge into about 0.28 with increasing valley size (Fig. 5). The value may correspond to the balance of vertical and lateral glacial erosion. The value also roughly corresponds to the threshold slope angle of V-shaped valleys with frequent slope failure (ca. 35° [8]), suggesting that erosion after deglaciation also plays a role in determining the convergent value of *FR*.

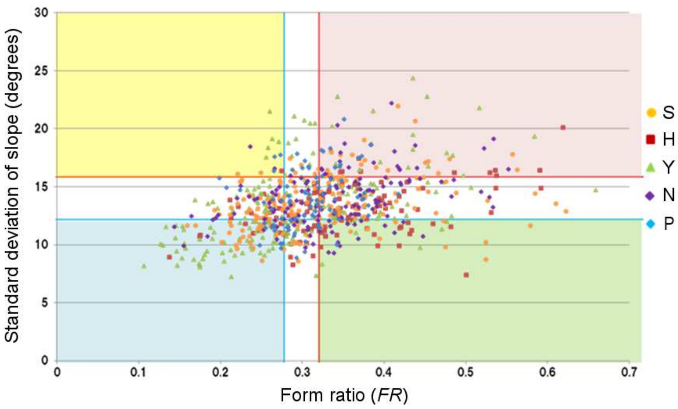

Figure 3. Relationship between the form ratio (*FR*) and standard deviation of slope (*Sd*) for all transverse sections analyzed. S: Swiss Alps. H: Himalayas. Y. Yosemite. N: New Zealand Southern Alps. P: Patagonia. Color zones are based on upper 30%, intermediate 40%, and lower 30% of each parameter values. Yellow zone: large *Sd*, small *FR*. Pink zone: large *Sd*, large *FR*. Blue zone: small *Sd*, small *FR*. Yellow-green zone: small *Sd*, large *FR*. White zone: intermediate *Sd*, intermediate *FR*.

TABLE III. PERCENTAGE OF THE TYPES OF TRANSVERSE SECTIONS IN EACH AREA. THE REST IS CLASSIFIED AS "OTHERS".

	U-shaped	V-shaped	Plain
Swiss Alps	25.7% (45/174)	12.6% (22/174)	23.4% (41/174)
Himalayas	27.1% (32/117)	28.8% (34/117)	17.8% (21/117)
Yosemite	22.1% (45/203)	9.3% (19/203)	30.9% (63/203)
NZ S Alps	31.9% (45/140)	18.4% (26/140)	9.9% (14/140)
Patagonia	26.4% (23/86)	16.1% (14/86)	11.5% (10/86)

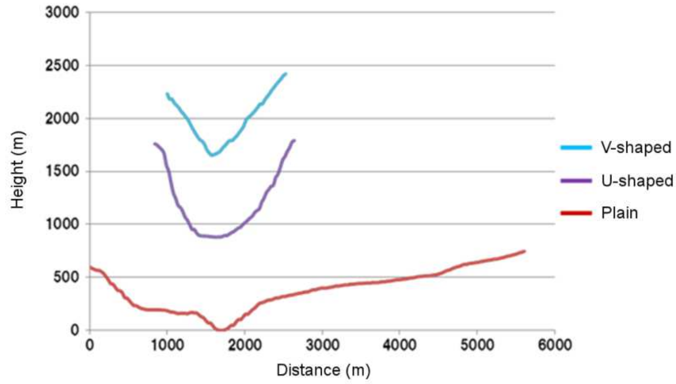

Figure 4. Typical examples of three types of valley transverse profiles.

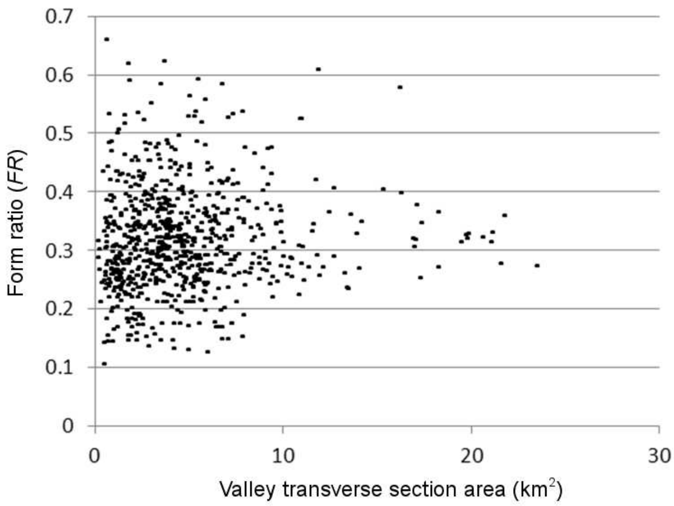

Figure 5. Relationship between the area of the valley transverse section and the form ratio (*FR*) for all transverse sections analyzed. *FR* tends to converge into ca.0.28 with increasing section area.

The correlation between the area of each transverse section and the equilibrium line altitude was also investigated. In each region, *FR* tends to change according to elevation, and reaches the maximum in an intermediate elevation in the Swiss Alps and areas around Mt. Cook in New Zealand (Fig. 6). The elevation approximately corresponds to the estimated equilibrium line altitude during the Last Glacial Maximum, suggesting a possibility of estimating the past equilibrium line from morphometric analysis of glacial valleys.

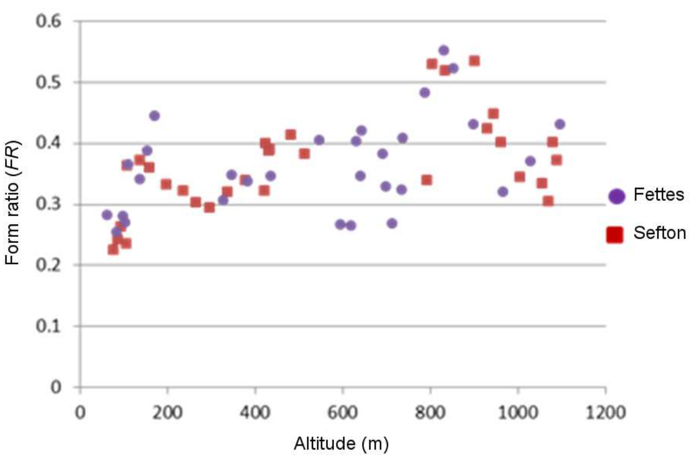

Figure 6. Relationship between altitude of the lowest point of each transverse section and the form ratio (*FR*) for the Fettes and Sefton glacial valleys near Mt. Cook, New Zealand. *FR* tends to be the highest at elevations around 900 m, which corresponds to the estimated equilibrium line altitude during the Last Glacial Maximum.

Future studies are needed to confirm the results of this paper and improve the quality of research. For example, whether a valley bottom consists of mostly bedrock or a valley fill may affect the determination of valley types, although this paper does not take it into account because of the lack of detailed information. Sampling of data also deserves future investigation. In this paper we sampled abundant transverse profiles from each valley, but it is also possible to sample less profiles per valley but from more valleys. The latter strategy may be suitable to discuss local- to meso-scale diversity of glacial valley forms.

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