Late Quaternary Equilibrium Line Altitude in the
Kiso Mountain Range, Central Japan

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Abstract: Geomorphological equilibrium line altitude (ELAg), as defined by steady-state equilibrium line altitude estimated based on geomorphological method, has been used to reconstruct Last Glacial palaeoclimate. However, the ELAg is influenced not only by temperature, but also by other factors. This paper discusses factors affecting Last Glacial ELAg in the Kiso mountain range, central Japan. The weathering-rind thickness of gravel was used for dating moraines. The dating results have shown that glaciers advanced at the Last Glacial Maximum and the Younger Dryas stages. The ELAg for each stage was reconstructed based on the Accumulation-Area-Ratio method (AAR = 0.6). The results indicate that the ELAg of each reconstructed glacier was affected not only by temperature but also by the altitude of mountain ridges. Although some previous studies have reconstructed palaeoclimate based on the ELAg, the results of the present study cast doubt on such reconstruction. For better reconstruction, the effects of temperature on the ELAg should be separated from those of topographic factors.

Key words: weathering-rind thickness, geomorphological equilibrium line altitude, glacial landform, the Last Glacial age, palaeoclimate reconstruction, central Japan

Introduction

The distribution of glacial landforms has been surveyed to reconstruct last-glacial palaeoclimate (e.g., Porter 1979; Clapperton 1983; Ono 1984; Yanagimachi 1987) and the reconstructed palaeoclimate based on glacial landforms has been discussed in terms of the "snowline" altitude. Ono (1984) and Yanagimachi (1987) described the altitude of the Last Glacial snowlines projected along the meridian as straight lines. These straight lines could be regarded as the representative value of the spatial tendency of the "orographic snowline altitude," corresponding to the regional snowline (Nogami 1970; Nogami and Ono 1981). The term of "orographic snowline altitude" means the altitude where the mass balance of the glacier equilibrates, and it is the same as the steady-state equilibrium line altitude (ELA0). However, it is hard to determine the palaeo-ELA0 because it is impossible to reconstruct the mass balance of past glaciers. Then the geomorphological equilibrium line altitude (ELAg) calculated based on the geomorphological method, substitutes the ELA0. ELAg have been estimated from the altitude of cirque floor (Flint 1947), altitude differences between glaciated summits and unglaciated summits (Imamura 1940), and the ratio of accumulation area to glaciated area (Charlesworth 1957; Ito and Vorndran 1983).

The altitude of the regional snowlines for Japanese glaciated mountains reconstructed by Ono (1984) and Yanagimachi (1987) corresponds to a northward decrease in temperature. This implies that the regional distribution of ELAg mainly depends on climatic factors, in particular on temperature distribution. However, topographical factors, such as the existence of flat erosion surfaces on mountains and the direction of the mountain ridges also affect the altitude of the ELAg of each glacier (Imamura 1940; Kobayashi 1958). The degree of glacial erosion often differs even between adjacent valleys and the climate played only a limited role in determining the ELAg in Japanese mountains (Imamura 1940). Consequently, it is necessary to separate the influence of topographical factors from that of temperature fac-
When we try to reconstruct palaeoclimate using glacial landforms.

Dating and correlation of glacial landforms are other problems. Iozawa (1979) and Ono and Hirakawa (1975) once identified two stages of glacial advance during the Last Glacial stage in Japanese Mountains. Further studies have revealed that glaciers advanced four times in central Japan during the Last Glacial stage (Table 1; Koaze et al. 1974; Ito and Vorndran 1983; Yanagimachi 1983; Hasegawa 1992; Aoki 1994). Lack of numerical dates on glacier advances, however, makes it difficult to correlate the stages of glaciation in various valleys and cirques in Japan. For example, although Ito and Masaki (1987) tried to correlate the Last Glacial ELA in two mountain ranges of central Japan based on the distribution of glacial landforms and their degree of dissection, they had to show two tentative correlations owing to limited dating information. Therefore, it is necessary to develop methods of correlation among glacial landforms.

This paper discusses the distribution and the age of glacial landforms in the Kiso mountain range in central Japan on the basis of weathering-rind thickness (WRT) of moraine gravel as an indicator of relative ages. Next, climatic and topographic factors influencing the geomorphologic equilibrium line altitude during glacial periods will be examined and discussed.

### Study Area

#### Physical settings

The Kiso mountain range, about 90 km long, is located in the central part of the Honshu Island. The granitic rock called Kisokoma granite underlies the Kiso mountain range and the property of the rock is almost uniform through the range (Shibata 1954). The Kiso mountain range is located at the present boundary of the climatic zone between the Pacific side type and the Sea of Japan side type and is situated on the southern limit of precipitation under the northwestern monsoon in winter (Suzuki 1962).

#### Previous research on glacial landforms

Iozawa (1979) pointed out that the glacial landforms in the Kiso mountain range were formed in two glacial stages mainly based on landform classification by air-photo interpretation. Some chronological studies of glacial landforms based on tephrachronology (Kobayashi and Shimizu 1966; Yanagimachi 1983) indicate that the two glacial stages correspond to the earlier and the latter half of the Last Glacial
stage respectively. Furthermore, Aoki (1994) examined the age of the glacial landforms in the latter stage using the WRT formed on morainic gravel. The results suggested that the glacial landforms in the latter stage could be classified into two stages: those formed in the Last Glacial Maximum (LGM) stage and those formed in the Younger Dryas (YD) stage (Table 1). The distributions of glaciers and ELA during the stages have not been examined in detail before.

**Methods of WRT Measurement**

The weathering-rind thickness (WRT) of the morainic gravel has been mainly used for dating glacial deposits. Radiocarbon dating and tephrochronology have been widely used for dating deposits in Japan. In high mountains, however, it is difficult to find humic layers or plant remnants suitable for radiocarbon dating because of the weak development of soil and vegetation in alpine zones. Moreover, tephra layers are generally absent in alpine zones because they can be eroded easily by strong winds and snowmelt water. For this reason, ages of landforms in alpine zones have often been estimated based on relative dating such as lichens and the WRT of gravel. The indices give the relative ages of landform within a relatively small area. However, such relative ages can be converted into numerical ages if other dating controls are available in the same area.

A weathering rind is the discoloration part near rock surfaces formed mainly by oxidation and hydration (Watanabe 1990). Birkeland (1973), Chinn (1981), Koizumi and Seki (1992) and Koizumi and Aoyagi (1993) estimated the formation ages of moraines and periglacial slopes by measuring the WRT of gravel. Aoki (1994) also applied this method to some moraines in the Kiso mountain range and analyzed the results on a statistical basis. Thus, the WRT method has been adapted to date morainic gravel in the study area.

In collecting data, the following criteria have been used to assure consistent sampling (Aoki 1994):

a: select the gravel of granodiorite
b: select gravel with a maximum diameter more than 20 cm
c: select gravel exposed on the surface of a moraine
d: select gravel less subjected to snow avalanche, snow accumulation and running water
e: select gravel not covered with vegetation
f: use weathering rinds developed on the upper side (sunny side) of gravel
g: avoid using weathering rinds at the corners or near the joints of gravel

The selected gravel was broken with a hammer to expose a fresh surface with weathering rinds. Next, the rind on the upper surface except for corners and near joints was divided into five parts, and maximum WRT for each part was measured using calipers to the unit of 0.05 mm. From five measured values, three values without maximum and minimum were averaged to calculate the WRT of each gravel. The WRT of 25 gravel was measured for each moraine following the criteria of Burke and Birkeland (1979). Wherever it was possible, the WRT of 50 gravel was measured.

**Results**

**Results of moraine identification and WRT measurement**

This chapter describes the results of WRT measurements for the selected 16 cirques (Figure 1). The results of the Nogaike cirque, Senjokiki cirque and San’nosawa cirques have already been described in detail in Aoki (1994).

**Tamanokubo cirques** (Figure 2-a): The Tamanokubo cirques consists of four cirques designated as Tamanokubo I-IV cirques from east to west. Terminal moraines can be found in each cirque and these moraines are designated as TAM-A, TAM-B, TAM-C and TAM-Du (Tamanokubo D upper moraine). Lateral moraines are preserved along glaciated valley below the Tamanokubo D cirque and one of these moraines is designated as TAM-Dl (Tamanokubo D lower moraine). The frequency distribution of WRT of these five moraines shows single mode except for TAM-C (Figure 3). Although TAM-C has a frequency distribution with two peaks, these peaks are not far apart from the mean of
Figure 1. Study area and location of studied cirques.

Nogaike (Figure 2-b): On the bottom of the Nogaike cirque, there are one critical terminal moraine (NOG-T), one lateral moraine (NOG-L) and two medial moraine ridges. The frequency distribution of WRT for NOG-T and NOG-L has a single mode around 6.5 mm, whereas that of the northern medial moraine (NOG-M) has boarded peak (Figure 3). Ono and Shimizu (1982) found the Pm-V (correlated to On-Ys, between DKP and AT; Machida and Arai 1992) from the top of the lateral moraine along the glaciated valley below the Nogaike cirque.

Senjojiki cirque (Figure 2-c): The detailed geomorphological map of the Senjojiki cirque has made by Yanagimachi (1983). According to this map, 15 moraines exist on the cirque floor including two terminal moraine (SEN-C and SEN-K) and 13 lateral moraines (SEN-B, SEN-E, SEN-I and others). Only SEN-B has a frequency distribution with two peaks, and that of the other moraines are single peaked.

San'nosawa cirques (Figure 2-d): The San'nosawa cirques are located on the western side of the main ridge. These cirques consist of three designated as San'nosawa I-III cirques from west to east. Terminal moraines can be found in each cirque and these moraines are designated as SAN-IU (San'nosawa I upper moraine), SAN-II and SAN-III. A lower terminal moraine is preserved within the glaciated valley below the San'nosawa I cirque and is designated as SAN-IL (San'nosawa I lower moraine). The frequency distribution of WRT of these moraines shows single mode except for SAN-IL.

Ikenotaira cirque (Figure 2-e): The Ikenotaira cirque is located on the northeast side of Mt. Kumazawa in the central part of the range. Moraines in this cirque are known as the glacial landform which was first dated in Japan based on tephrochronology (Kobayashi and Shimizu 1966). Three moraines are preserved in the
Figure 2. Distribution of glacial landforms of study area.
(a) Tamanokubo cirques, (b) Nogaike cirque, (c) Senjojiki cirque, (d) San’nosawa cirques, (e) Ikenotaira cirque, (1) investigated moraine, (2) uninvestigated moraines, (3) distinct cirque wall and reconstructed glacial tongue, (4) distracted cirque wall and reconstructed glacial tongue, (5) calculated ELA$_g$ in YD stage, (6) calculated ELA$_g$ in LGM stage.

Name of investigated moraines
1 TAM-A, 2 TAM-B, 3 TAM-C, 4 TAM-Du, 5 TAM-Dl, 6 NOG-T, 7 NOG-L, NOG-M, 9 SEN-B, 10 SEN-C, 11 SEN-E, 12 SEN-I, 13 SEN-K, 14 SAN-Iu, 15 SAN-Ic, 16 SAN-II, 17 SAN-III, 18 IKE-A, 19 IKE-B, 20 IKE-C.

† is the same as Figure 1.
The frequency distribution of WRT for IKE-B and IKE-C has a single mode, whereas that of IKE-A has two peaks around 6.0 mm and 8.5 mm (Figure 3).

**The other cirques:** Furthermore, landforms of five more cirques in the Kiso mountain range (Hosoozawa, Komakainoike, Akanagidake-Kita, Suribachikubo and Suribachikubo-Minami cirques) were classified based on air photograph interpretation. Iozawa (1979) also identified all of them as cirques. WRT measurement from these cirques was not carried out because of the difficult accessibility and/or lithological problems. The ages of moraines in these cirques were estimated based on the degree of landform dissection and location of moraines.

**Classification of moraines based on WRT values**

The results of WRT measurement of each moraine are compiled in Figure 3 and Table 2. This figure shows that the WRT values from 20 moraines in 5 cirques can be divided into 3 groups; Group 1, the peak of WRT value located between 8–9 mm; Group 2, between 6–7 mm and Group 3, between 4–5 mm.

The validity of this grouping was investigated based on rank sum test (Kruskal–Wallis test), non-parametric statistical tests to assure the difference between two or more groups. The Kruskal-Wallis test is considered to be effective for classifying landforms using WRT (Fusejima 1993; Aoki 1994). To examine the significance of the division of groups, WRT values for IKE-A (with the smallest mean WRT among moraines correlated to the Group 1) and those for SEN-E (with the largest WRT among moraines correlated to the Group 2) were first analyzed by this test. The results have shown that the difference between WRT values for the two moraines is significant at a 97.5% level (Table 3). Similarly, the difference between WRT values for SAN-IIL (with the smallest mean WRT among correlated to the Group 2) and those for SEN-K (with the largest mean WRT among moraines correlated to the Group 3) is significant at a 97.5% level.

Next, the significance of moraine correlation within the same stage was examined. The results of the test confirm with 97.5% confidence
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Table 2. Results of WRT measurement of each moraine

| Moraine Name   | AVG (mm) | STD | Mode (mm) | N | Group |
|----------------|----------|-----|-----------|---|-------|
| (a) Tamanokubo cirques |          |     |           |   |       |
| TAM-A          | 4.2      | 0.6 | 4.5       | 25| 3     |
| TAM-B          | 4.3      | 0.5 | 4.5       | 25| 3     |
| TAM-C          | 4.2      | 0.5 | 4.0/5.0   | 25| 3     |
| TAM-D$_L$      | 4.4      | 0.5 | 4.5       | 25| 3     |
| TAM-D$_H$      | 5.9      | 0.6 | 6.5       | 25| 2     |
| (b) Nogaike cirques |        |     |           |   |       |
| NOG-T          | 6.2      | 0.6 | 6.5       | 50| 2     |
| NOG-M          | 6.5      | 0.8 | 6.5       | 25| 2     |
| NOG-L          | 5.6      | 1.2 | 7.0       | 25| 2     |
| (c) Senjoji cirques |       |     |           |   |       |
| SEN-B          | 7.8      | 1.0 | 8.5       | 25| 1     |
| SEN-C          | 6.6      | 0.6 | 7.0       | 25| 2     |
| SEN-E          | 6.7      | 1.0 | 7.0       | 25| 2     |
| SEN-I          | 6.3      | 0.5 | 6.5       | 25| 2     |
| SEN-K          | 4.4      | 0.4 | 4.5       | 15| 3     |
| (d) San'nosawa cirques |    |     |           |   |       |
| SAN-IU         | 4.3      | 0.5 | 4.5       | 50| 3     |
| SAN-IL         | 5.4      | 0.8 | 6.0       | 50| 2     |
| SAN-II         | 6.3      | 0.7 | 6.5       | 50| 2     |
| SAN-III        | 6.5      | 1.0 | 6.5       | 50| 2     |
| (e) Ikenotaira cirques |      |     |           |   |       |
| IKE-A          | 7.6      | 1.0 | 8.5       | 25| 1     |
| IKE-B          | 6.1      | 0.5 | 6.5       | 25| 2     |
| IKE-C          | 4.0      | 0.3 | 4.5       | 12| 3     |

AVG: Average thickness of weathering rind
STD: standard deviation of WRT
Mode: mode of frequency distribution of WRT
N: number of sampling gravel
Group: see text

that the moraines correlated to Group 1 and Group 3 were formed in the same period (Table 3). On the other hand, the same test has shown that the correlation of moraines to Group 2 is not significant at 97.5% confidence level (Table 3). The test for moraines correlated this group except for SAN-I$_L$ and NOG-M with markedly irregular frequency distribution has shown that the age of moraine formation can be subdivided into two sub-stages. However, if the test is performed for two moraines with closest averages WRT values, no pairs are significantly different (Table 3). This fact indicates that moraines correlated to Group 2 were formed successively (Figure 4). The above examinations have shown that the correlation of moraines into three groups is acceptable.

The numerical age of glacial stages

As shown in the former section, observed moraines can be divided into three groups, and this means that three glacial stages existed. It is important for discussion to clarify the numerical age of these glacial stages.

Within the study area, Yanagimachi (1983) estimated the ages of moraines in the Senjoji cirque based on tephrachronology. In the valley below the cirque, Yanagimachi (1983) discovered an aeolian tephra called Pm-IV (43–55 ka, Machida and Arai 1992) at just the top of the gravel forming the Shirabidaira I terrace. This terrace stands higher than the Shirabidaira II terrace, whose gravel was accumulated as a ground moraine slightly before SEN-B was formed. The valley glacier that had formed Shirabidaira II terrace formed SEN-B moraine after retreating. On the Shirabidaira II terrace, Pm-IV could not be found. This means that SEN-B was formed after the fall of Pm-IV. The numerical ages of SEN-C and NOG-T are determined by Aoki (2000) with the $^{10}$Be exposure dating method. The result of these studies showed that these moraines formed during 18–20 ka. Moreover, samples of Aoki (2000) were taken from top of the moraine, then the values of WRT correspond to the $^{10}$Be exposure age. These results indicate that the moraine forming
age of Group 1 including SEN-B is about 40 ka (the end of former half of the last glacial stage) and that of Group 2 including SEN-C and NOG-T is around 20 ka (the Last Glacial Maximum; LGM). The moraines in Group 3, which has the smallest WRT values, have younger age than Group 2. However, it is difficult to decide the age of the glacial stage of Group 3 because there is no numerical dating from these moraines at present.

Igarashi et al. (1993) pointed out the existence of the cooler period during the Younger Dryas (YD) stage in Hokkaido Island. Sakaguchi (1978) and Yasuda (1978) also suggested the cooler event during Late Glacial stage. Moreover, Aoki et al. (1998) and Aoki (Submitted) suggested that some moraines in the Hida mountain range might be formed during the YD stage based on the $^{10}$Be exposure age. According to these results, the glacial stage of Group 3 may correspond to the YD stage temporarily. In the next chapter, the author discusses the moraines belonging to Group 3 as being formed during the YD stage.

### Discussion

#### Determination of geomorphological equilibrium line altitude

$ELA_x$ is an important index for discussion of the spatial distribution of the reconstructed glaciers. The AAR method (the Accumulation-Area-Ratio method, defined by Charlesworth 1957) is one of the methods to calculate the $ELA_x$ from glacial landform, and the altitude calculated with this method has been considered to be the best fit to the “steady-state equilibrium line altitude ($ELA_0$)” of the modern glaciers (Hawkins 1985). Although this method may include some errors (Nogami 1970), it is useful to deal with many glaciers using the same criterion. Aoki (1999) discussed the AAR value, for reconstruction of the $ELA_x$ based on the mass balances data from the modern glaciers in the world and confirmed that the steady-state AAR ($AAR_0$) of modern glaciers converges to 60%. Therefore, the AAR method with AAR value of 60% was applied to reconstruct the $ELA_x$ of the cirques in the study area (Table 4).

The distributions of glaciers in the LGM and
Table 4. Glacial Inventory of the Kiso Mountain Range

| LGM Glacier     | Area (km²) | ELAₘ (m) | Hₛ (m) | Terminus Alt (m) | Hₛ-ELAₘ (m) | Latitude (deg) | YD Glacier     | Area (km²) | ELAₘ (m) | Hₛ (m) | Terminus Alt (m) | Hₛ-ELAₘ (m) | Latitude (deg) |
|-----------------|------------|----------|--------|------------------|-------------|----------------|----------------|------------|----------|--------|------------------|-------------|----------------|
| Tamanokubo D    | 0.206      | 2460     | 2733   | 2240             | 273         | 35.79          | Tamanokubo D   | 0.081      | 2600     | 2733   | 133               | 35.79       |                |
| Tamanokubo C    | 0.063      | 2575     | 2676   | —                | —           | 35.79          | Tamanokubo C   | 0.063      | 2575     | 2676   | 101               | 35.79       |                |
| Tamanokubo B    | 0.054      | 2630     | 2800   | 2480             | 170         | 35.79          | Tamanokubo B   | 0.054      | 2630     | 2800   | 170               | 35.79       |                |
| Tamanokubo A    | 0.068      | 2700     | 2826   | 2530             | 126         | 35.79          | Tamanokubo A   | 0.068      | 2700     | 2826   | 126               | 35.79       |                |
| Hosoozawa       | 0.350      | 2710     | 2956   | 2400             | 246         | 35.79          | Hosoozawa      | 0.146      | 2740     | 2956   | 2520             | 216         | 35.79          |
| Nogaike         | 0.108      | 2680     | 2870   | 2640             | 190         | 35.79          | Nogaike        | 0.038      | 2710     | 2870   | 2540             | 160         | 35.79          |
| Komakaiike      | 0.151      | 2870     | 2925   | 2630             | 55          | 35.78          | Komakaiike     | 0.060      | 2790     | 2925   | 2700             | 135         | 35.78          |
| Senjojiki       | 0.559      | 2690     | 2931   | 2220             | 241         | 35.78          | Senjojiki      | 0.131      | 2740     | 2931   | 2560             | 191         | 35.78          |
| San'nosawa III  | 0.011      | 2715     | 2889   | 2560             | 174         | 35.77          | San'nosawa III | —         | —        | —     | —                | —           |                |
| San'nosawa II   | 0.096      | 2640     | 2676   | 2560             | 36          | 35.77          | San'nosawa II  | 0.052      | 2720     | 2800   | 2610             | 80          | 35.77          |
| San'nosawa I    | 0.068      | 2710     | 2800   | 2530             | 90          | 35.77          | San'nosawa I   | 0.052      | 2720     | 2800   | 2610             | 80          | 35.77          |
| Ikenotaira      | 0.065      | 2600     | 2720   | 2520             | 120         | 35.74          | Ikenotaira     | 0.051      | 2625     | 2720   | 2550             | 95          | 35.74          |
| Akanagidake     | 0.174      | 2670     | 2797   | 2380             | 127         | 35.70          | Akanagidake    | —         | —        | —     | —                | —           |                |
| Suribachikubo   | —          | —        | —      | —                | —           | —              | Suribachikubo  | 0.113      | 2685     | 2839   | 2550             | 154         | 35.70          |
| Sengairei       | 0.197      | 2540     | 2760   | 2330             | 220         | 35.69          | Sengairei      | 0.068      | 2600     | 2700   | 2470             | 100         | 35.69          |
YD stages were reconstructed based on the positions of moraines and the break of slopes on the cirque walls. Next, the area of each glacier was measured on 1/5,000 topographic maps using a digitizer. The calculated ELA_g for dated cirques are illustrated in the Figure 2.

Problems in reconstructing regional snowlines using geomorphological equilibrium line altitude

Hoshiai and Kobayashi (1957) and Rathjens (1982) have assumed that the present regional snowline projected along the meridian from 30°N to 70°N can be expressed by a straight line inclining to the north, since the regional snowline over the middle latitude is a function of temperature. Moreover, Yanagimachi (1987, 1991) and Yanagimachi and Ohmori (1991) pointed out that the altitude of the present regional snowline over the Japanese Islands is almost the same as 4–5°C in summer season (July and August), and the results of the aeronautical observation indicate that the altitude of the isotherm over the Japanese Islands inclines to the north (Yanagimachi 1987).

Figure 5 shows the ELA_g of each reconstructed glacier for the LGM and YD stages, projected on the latitude section. There is a significant variation in the ELA_g among different mountains. This variation is more distinct for the ELA_g in the LGM stage than that in the YD stage. In particular, the ELA_g for the Tamanokubo cirque group during the YD stage is remarkably lower than that for the other cirques. The straight lines on Figure 5 show the regression lines fitted to values of ELA_g during the LGM (solid) and YD (dashed) stages projected along the meridian. When straight lines are fitted to the data for the LGM and YD stages, the correlation of the fitting is low (LGM, r² = 0.305; YD, r² = 0.312). This means that these regression lines do not represent the ELA_g of each cirque in the Kiso range. Moreover, the regression lines for both stages decline to the south, which opposes to the trend of the present regional snowline. Consequently, it is likely that the ELA_g of each cirque was determined not only by temperature but also by other factors.

Factors influencing geomorphological equilibrium line altitude

It is well known that most glacial landforms in Japan are located on the eastern side of mountain ridges. This also applies to the glaciers in the Kiso mountain range. As pointed out by Kobayashi (1958), this mode of glacial distribution was dominated by frequent northwesterlies in winter. At present, the winter monsoon blowing over the Japanese mountains has one of the largest velocity values in the world (Haestie and Stephens 1960). Such strong northwesterlies also prevailed during the Last Glacial stage in central Japan (Yoshino and Urushibara 1977; Ono 1984). The strong winter monsoon was able to transport abundant snow to leeward slopes, resulting in distinct development of glaciers on the east side of the ridges. Such abundant snow accumulation at eastern slopes generally occurs in a limited...
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Figure 6. Relationships between geomorphological equilibrium line altitude (ELAg) and mountain ridge altitude (Hs). Solid and dashed lines indicate the fitting line.

Table 5. Statistical results of relationship between ELAg and Hs

| Stage | a   | b   | r²  |
|-------|-----|-----|-----|
| LGM   | 0.749 | 544.76 | 0.450 |
| YD    | 0.696 | 721.57 | 0.838 |

a, b: values in equation "y=ax+b"
r²: decision coefficient.
"a" indicates the cline of the fitting line. When this value is 1, the relative heights from ELAg to Hs do not depend on the change in Hs. When this value is 0, ELAg is fixed regardless of the change in Hs.

zone close to the ridge. This fact suggests that the distribution of past glaciers should be also confined to the zone near the ridge.

To test the validity of the above hypothesis, the relation between the altitude of ridge and the ELAg was examined. The altitude of the mountain ridge is represented to the altitude of the highest point surrounding the accumulation area of the reconstructed glacier (Hs). Table 4 shows the database for calculation. Then, the relationship between Hs and ELAg was examined (Figure 6). The results have shown that these two properties are positively correlated (Table 5). The both fitting lines during LGM and YD stages are almost in accord with each other, in spite of the ELAg of each reconstructed glacier which had risen up from the LGM stage to the YD stage. This means that ELAg of each reconstructed glacier was strongly affected by the mountain ridge altitude behind the cirque regardless of the temperature change. Moreover, the ELAg of each reconstructed glacier was located in a fixed range of 200 to 250 m from the mountain ridge except for Tamanokubo D glacier during the LGM stage. These observations validate the hypothesis that past glaciers tended to be located in a limited zone close to the ridge. In other words, topographic factors played an important role in determining the ELAg of each glacier. Nogami (1969) has also pointed out a high correlation between the altitude of the cirque bottom and the summit altitude for the Andes Mountains and suggested that the cirque bottom altitude does not represent the regional snowline altitude of the respective region. His observation agrees with the results of the present study.

Although topography is the major factor controlling the ELAg of each reconstructed glacier, the results of this study indicate that temperature conditions also affect the ELAg to the same degree. The gradient of linear functions describing the ELAg-Hs relation is less than 1.0, showing that ELAg tended to locate closer to the ridge as the altitude of the ridge decreases (Table 5). This observation likely reflects temperature increase with decreasing altitude, since higher temperature was unfavorable for glaciers to extend down to lower valleys.

Conclusion

This paper has discussed factors affecting the geomorphological equilibrium line altitude (ELAg) of glaciers during the latter half of the Last Glacial stage in the Kiso mountain range, central Japan. The weathering rind thickness of gravel was used for dating the ages of moraines. The dating results have shown that this age of moraines can be divided into three different stages, such as the former half of the Last Glacial stage, LGM stage and the YD stage. The ELAg for each stage has a strong relation to the
altitude of mountain ridges. This implies that the glacier development in the Kiso range has been dominated by snow accumulation transported by strong westerlies in winter on the eastern slope near the ridge. The ELA$_g$ for each reconstructed glacier should be affected mainly by topographic factors. For better reconstruction of palaeoclimate based on the glacial landforms, it is necessary to know the representative snowline altitude controlled by climatic factors. Palaeoclimate in the Japan Alps inferred from such a separation method will be reported elsewhere.

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Notes

1. The usage of the “snowline” is in confusion. Because it is an inappropriate as a technical term, it is necessary to put the meaning in order.
2. The regional snowline corresponds to the climatic snowline (Nogami and Ono 1981). This term is defined as the snowline without influences of the local topographic factor and/or slope direction, and its altitude directly reflects climatic factors, especially temperature. This definition is, however, conceptual and not strict.
3. ELA$_g$ is the equilibrium line altitude when the steady-state mass balance of the glacier is supposed (Benn and Evans 1998). This value is reported in “Glacier mass balance bulletin” (e.g., Haefelri and Herren 1991). It is necessary for calculating the ELA$_g$ to measure the annual ELA and annual mass balance of each glacier.
4. As usual, ELA$_g$ was called as “Orographic Snowline Altitude.” The term of “Orographic Snowline Altitude” is, however, abstract and the definition is not clear. Then, in this paper, the author defines the ELA$_g$ as a new technical term based on the calculation method. Originally, the term of “Orographic Snowline Altitude” includes two meanings, one is the “ELA$_g$ of each glacier” and the other is “ELA$_g$ affected by local topography, which is in contrast with the regional snowline” (e.g., Ono 1981). The term of “ELA$_g$” corresponds to the former meaning of the “Orographic Snowline Altitude.”

5. Only the ELA$_g$ of Tamanokubo D glacier during the LGM stage locates over 250 m high apart from H$_s$. There are large present landslides at the headwalls of the River Nameri valley (Mt. Mugikusa-dake landslide), across the ridge between the Tamanokubo D glacier and the valley. The ridge between both valleys also collapsed remarkably. Then, the headwall erosion of the River Nameri valley might dissect the accumulation area of this glacier during Holocene. In this case, the ELA$_g$ calculated based on the AAR method dropped lower than that of the true altitude. The author considered that this might well have affected the value of the Tamanokubo D glacier.

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