Estimating the Occurrence Ages of Deep Catastrophic Landslides using a Tephrochronological Approach

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We estimated the occurrence ages of deep catastrophic landslides (DCL) using a tephrochronological approach in the Chiroro River of the Saru River system, Hokkaido. Nine DCL scars were identified using aerial photo interpretation and LiDAR data analysis. Most of DCL scars were located near knick lines associated with the geomorphic development of the Hidaka Mountains. Based on a field investigation of soil profiles and tephra deposits, we revealed six DCL scars were formed before 9,000 yrs ago associated with the presence of Ta-d stratification. The remaining DCL scars were formed 9,000-2,500 yrs ago and in the past 300 years as determined by the presence of Ta-c, Ta-a, and Ko-c2. Based on an analysis of volcanic glass, the mixture of tephra suggested the occurrence of soil movement via soil creep and small failures at DCL scars following the formation of these features. Our approach permitted us to identify the formation of DCL scars from various periods ranging from centuries to millennia.

Key words: deep catastrophic landslide, tephrochronology, volcanic glass analysis

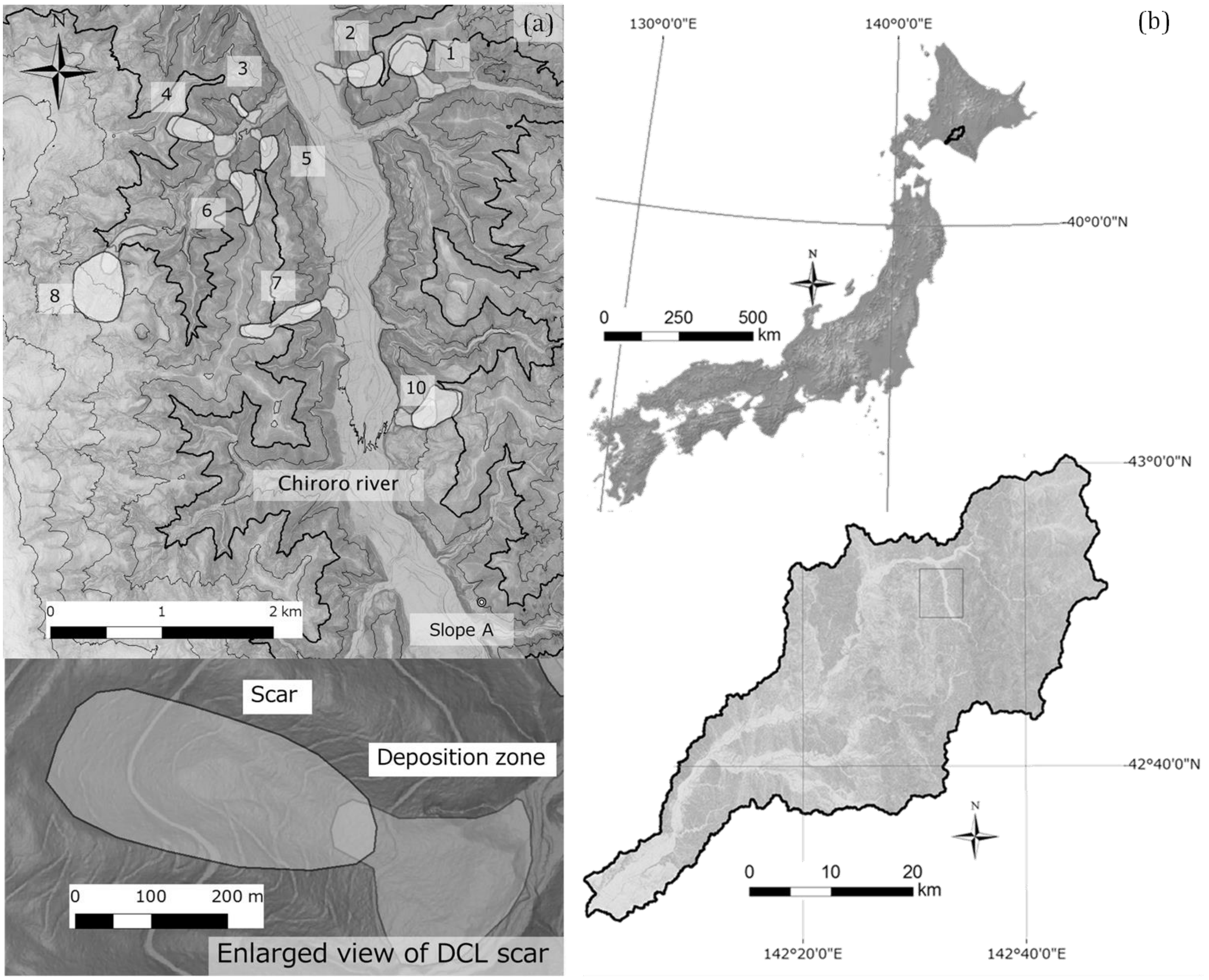
1. INTRODUCTION

The number of occurrences of deep catastrophic landslides (DCL) has increased in Japan over the past 30 years [*Uchida*, 2011]. The Japanese government has since put effort into developing the countermeasures for DCL and into the regional planning for disaster mitigation. Various ongoing assessments are being conducted in Japan including the identification of potential hillslopes for DCL [*Jitousono et al.*, 2006; *Yokoyama et al.*, 2011] and the prediction of subsequent debris flow and the formation of landslide dams.

Examining the distribution and frequency of DCL is critical for developing disaster prevention and management strategies [*Uchida and Nishiguchi*, 2011]. The occurrence and distribution of DCL in Japan over the last 120 years were investigated using publications, reports, and local records [*Public Works Research Institute*, 2010]. These data revealed that DCL tend to occur in regions with high tectonic uplift rates [*Uchida*, 2011] and the probability density of DCL has been qualified into four classes from high to low by the *Cabinet Office of Japan* [2013]. Although this information is helpful in identifying the regional characteristics of DCL, specific frequencies of DCL occurrence have not been identified. Moreover, because the frequency of DCL can be low, occurring at centurial to millennial scales, estimation of the ages of DCL is technically difficult.

To estimate long-term, low-frequency geomorphic activities, various methods have been used, including ^{14}C radioactive dating [*Akther et al.*, 2011], dendrochronology [*Alestalo*, 1971], cosmogenic radionuclide dating [*Lal et al.*, 1991] and tephrochronology [*Thorarinsson*, 1970]. Among these methods, tephrochronology is the most advantageous for estimating the age of specific landslide features. In general, tephra are deposited evenly, and the age of index tephra has already been identified by radiometric dating.

Tephrochronology has been applied in investigating the age sequence of hillslope stability in those areas with multiple tephra deposits. For



(Note: Thick contours represent elevation changes of 600 m, and thin contours represent 100-m intervals.)

Fig. 1 Study site and ten DCL scars in the Chiroro River basin (a) within the Saru River system (b)

example, *Yanai and Usui* [1989] estimated the periodicity of the occurrence of shallow landslides from 50 to 150 yrs ago on the Pacific coast of Hokkaido. *Shimizu and Hatanaka* [2010] estimated that slope failure has occurred approximately every 650 years since 8,000 yrs BP in a small watershed of the Saru River system.

Despite the application of tephrochronology in assessing hillslope stability, such a method has not been applied in determining the ages of scar and deposition topography of DCL. Therefore, the objectives of this study were (1) to identify the geomorphic characteristics of DCL that have occurred in the past, and (2) to estimate the ages of DCL using tephrochronological approaches. We developed the appropriate methods and tested their applicability to determining DCL age over time scales from recent centuries to millennia.

2. STUDY SITE

This study was conducted in the Chiroro River basin and adjacent areas of the upper Saru River systems in the eastern Hidaka Mountains region of Hokkaido, Japan (**Fig. 1**). The drainage area of the Saru River system is 1,350 km^2, and the total channel length is 104 km. We selected 34.1-km^2 area for investigating DCL topography and tephra deposits. Mean annual precipitation and mean annual temperature were 1,292 mm and 6°C, respectively. The underlain geology of this area is complex, with marine sedimentary rocks and accretionary complex (basalt blocks, ultramafic rocks and chert blocks) around mountainous areas and non-marine sedimentary rocks around rivers.

Several index tephra are potentially distributed around the study areas [*Machida and Arai*, 1992]. These tephra were originated from the volcanic mountains in southwest Hokkaido including Mt. Tarumae, Mt. Eniwa-dake, and Mt. Komaga-take. The tephra indices from Mt. Tarumae were Ta-a in A.D. 1739, Ta-b in A.D. 1667, Ta-c in 2,500 yrs BP, and Ta-d at 9,000 yrs BP [*Machida and Arai,* 1992]. Tephra from Mt. Eniwa-dake have been indexed as

Table 1 Scales and geomorphologic characteristics of nine DCL scars

No.	Altitude of scar(m)	Mean slope(°)	Area ($\times10^4$ m^2)	Volume ($\times10^5$ m^3)	Underlaid geology	List of Tephra observed	Volcanic glass analysis
1	650	35	10.0	13.7	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c, Ta-d	
2	630	35	8.5	10.3	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c	
3	525	34	1.6	0.9	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c, Ta-d	○
4	642	31	7.0	7.9	Mafic volcanic rock (accretinary complex)	Ta-a, Ko-c2, Ta-c, Ta-d	
5	601	37	4.2	3.7	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c, Ta-d	
6	710	39	8.0	9.5	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c, Ta-d	
7	720	33	12.5	18.3	Marine sedimentary rock	no tephra	
8	805	24	23.5	45.4	Ultramafic rock	not surveyed	
10	630	31	11.7	16.6	Marine sedimentary rock	Ta-a, Ko-c2, Ta-c, Ta-d	○

(Note. Collapse volumes were calculated using Guzzetti's formula [Guzzetti et al., 2009].)

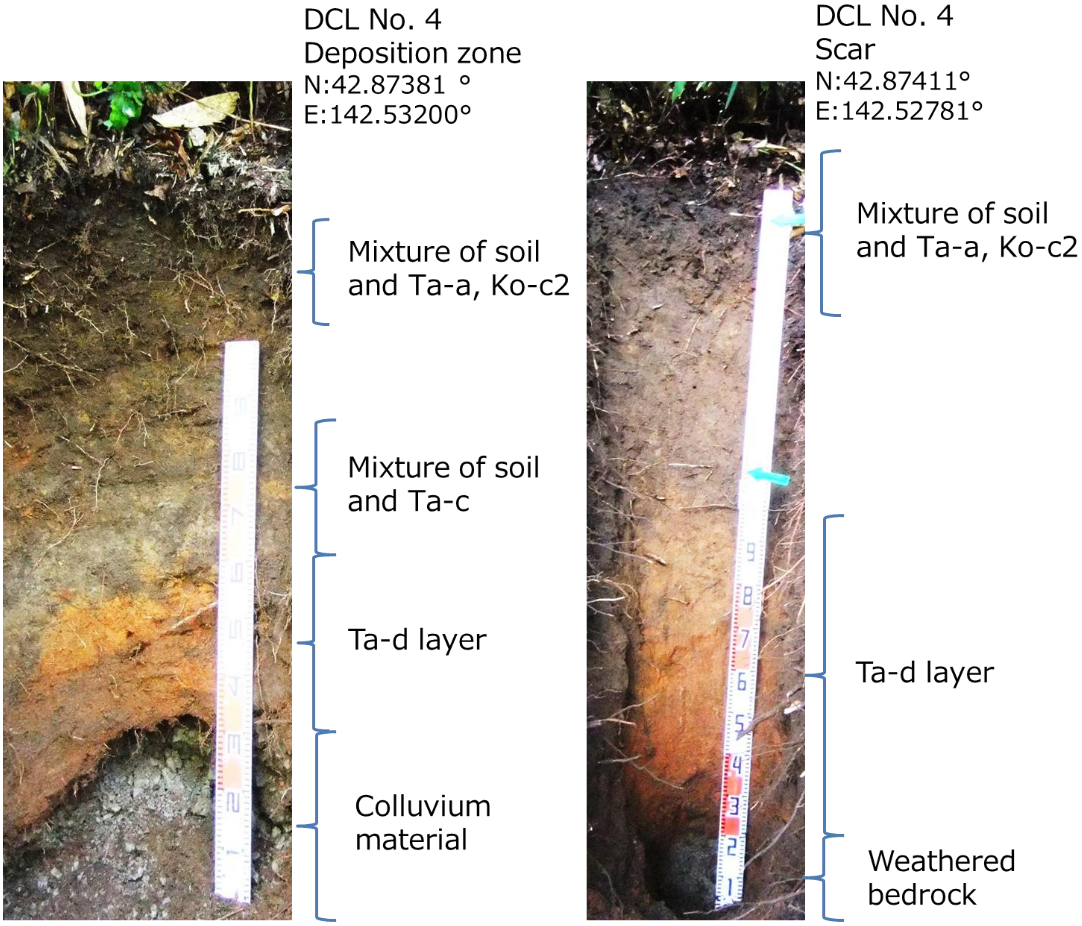


Fig. 2 Example for the soil profile in scar and deposition zones of DCL

En-a deposited from 16,000 to 19,000 yrs BP [*Umetsu*, 1987; *Kato*, 1994]. Ko-c2 originated from Mt. Komaga-take in A.D. 1694 [*Machida and Arai*, 1992].

3. METHODOLOGY

3.1 Topographic features of DCL scars

Topographic features potentially formed by past DCL were identified using aerial photographs taken

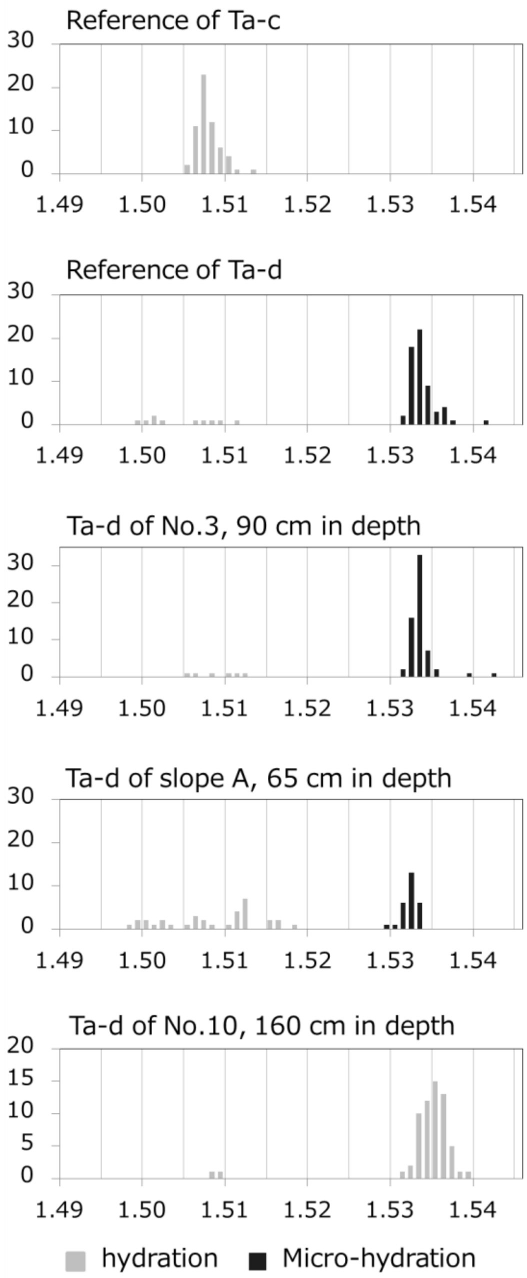


Fig. 3 Frequency distribution of refractive indexes

in 2007 (1:16,000 scale) and LiDAR data taken in 2012. We defined topographic features as DCL when they were characterized as a "large-scale collapse in which slide surface becomes deep compared to shallow rapid landslides and may reach to deep bedrocks. Collapsed soil of the scars can be mobilized to lower part to hillslope and most of them did not remain on scar surface [*PWRI*, 2008]". Both a concave depression zone and the fan-shaped topography of a deposition zone were identified in aerial photos and LiDAR data. Each extracted DCL scar and deposit zone were archived using ArcGIS (ESRI, Inc.) to analyze topographic parameters such as area, volume, height, altitude, and slope gradient.

3.2Field survey

Selected DCL features were field surveyed. In the field, we identified a concave depression in the scar and fan-shaped topography in the deposits of DCL. In both scar and deposition zones, we investigated soil stratification and texture by excavating 1 to 2 m in depth until reaching either bedrock or gravel (deposited by landslides) if they were available. Sequences of soil and tephra layers were identified in the bottom layers of the soil pits. Additionally, we recorded the thickness, depth, state of the mixture of soil and tephra, and the texture. We also collected soil and tephra samples for an analysis of detailed texture and volcanic glass. To determine a reference soil condition, we investigated tephra deposits and the soil sequence of soils flat areas, slopes and mountain ridges within our study area. Similarly, we examined the soil profile of an outcrop of Bibi in Chitose City, Hokkaido, to provide a reference for Ta-a, Ko-c2, Ta-c, and Ta-d layers. We observed a clear stratification of tephra in this area because of its location near source volcanoes.

3.3 Analysis of tephra

Most of the index tephra were identified in the field based on their stratification, depth, particle sizes, and color. We then confirmed some of the tephra layers using volcanic glass analysis. Volcanic glass is fine-particle magma formed by rapid cooling and crushing in volcanic eruptions. Characteristics of volcanic glass, such as its form and refractive index, can be used to indentify eruption type and the chemical and physical properties of magma. Therefore, volcanic glass analysis was used to identify the source volcano and DCL age [*Furusawa*, 1995].

Samples were dried for 15 hours at 50°C and then washed using ultrasonic cleaning. The volcanic glass was classified into seven types: flat type (Ha and Hb), middle type (Ca and Cb), porous type (Ta and Tb), and additional forms not included in the above types (It) [*Yoshikawa*, 1976]. Hydration phenomena that indicate weathering rates were classified as hydrated or micro-hydrated [*Nakamura et al.*, 2002]. We estimated refractive indices using the Refractive Index Measuring System [*Yokoyama et al.*, 1986], and analyzed samples from selected DCL scars and reference sites. All analysis was conducted by Kyoto Fission-Track Co., Ltd.

4. GEOMORPHIC CHARACTERISTICS

We identified nine geomorphic features potentially formed by past DCL. All of the landslide features had both scars and deposits located adjacent to each other. The altitude of the tops of DCL scars ranged from 525 to 805 m (mean: 657 m). The mean slope gradient of scars ranged from 24° to 39° (mean: 33°), and mean slope gradient in the deposition zone ranged from 16° to 30° (mean: 24°). DCL scars were within the ranges of DCL previously reported in Japan (30° to 35°) [*Uchida et al.*, 2010]. Areas of DCL scars ranged from 1.6 x 10^4 to 2.4 x 10^5 m^2. The ranges of DCL areas were similar to those of recent DCL that have been identified to have occurred within the past 100 yrs in Japan. Seven DCL scars among the 10 identified were located within marine-sedimentary rock strata, and two DCL scars were within ultramafic strata and accretionary complex strata.

The upper ends of the DCL scars were located near the knick line, which was distributed at 600 m altitude (approximately 200 m from the terrace of the upstream area of the Saru River system) based on LiDAR topographic data. Therefore, most of DCL scars crossed the knick lines. These findings are in agreement with those of *Ishimaru et al.* [2008] in the Atsubetsu River watershed.

Long-term slope stability may also depend on the lower and upper parts of knick lines. For example, *Shimizu et al.* [1995] showed, using tephra analysis, that the stabilities differed between the upper and lower slopes that were divided by knick lines. They demonstrated that the upper part of knick lines can remain stable for more than 8,000 yrs. In general, knick lines were formed by long-term geomorphic evolution during the Quaternary period [*Yanai*, 1989]. Therefore, the occurrence of DCL may be associated with long-term geomorphic deformation

Topographic investigation of the DCL scars and identification of knick lines confirmed that the occurrence of DCL can be associated, in part, with long-term geomorphic deformation. *Chigira* [2009] showed that gravitation deformation and the formation of bedrock fractures are signatures for the potential occurrences of DCL. *Uchida et al.* [2011] showed that gentle ridge and liner depression can be important factors in DCL occurrence. We also confirmed similar characteristics of DCL and of the surrounding areas as presented by *Uchida et al.* [2011].

5. OCCURRENCE AGES

As a reference condition, Ta-a consisted of white fine sand with no distinctive layer. Because the amount of Ta-a fallout in our study site was small, most of the Ta-a was mixed with surface soil and litter. The deposit volume of Ta-b was trivial and could not be identified in given soil pits. The Ta-c layers and lumps were less than 1 cm thick and occurred at 10–50 cm in soil depth. Ta-d having fine reddish brown pumice was identified clearly as approximately 40-cm thick and was located at 60–100 cm in soil depth. Although Ko-c2 was located around our study site [*Machida and Arai*, 1992], a mixture with Ta-a near the soil surface made it difficult to identify the specific layer. In the slope adjacent to DCL No. 10, we also found a 30-cm thick En-a with yellowish brown fine pumice at 130-cm soil depth.

Soil profiles were measured in the scars and deposition zones of nine DCL scars. Colluvium material layers which included coarse fragment rocks and gravels were found at 30–170cm the soil depth in deposition zones. Weathered bedrock layers were found at 20–200cm soil depth in scar zones of four DCL. Likewise, the thickness of soil varied depending on the scar and the deposition zone. Ta-d deposits were found above colluvium materials or weathering bedrock in six DCL features (**Table 1, Fig. 2**). No mineral soil horizon was found between the bottoms layers of Ta-d and bedrock or colluvium materials. Therefore, those DCL with Ta-d may have occurred just before the occurrence of Ta-d fallout. The possibility of DCL occurring more than 9,000 yrs ago relates to the instability of hillslopes due to climate changes. *Shimizu* [1989] and *Yanai and Usui* [1989] also found that hillslope materials from between 18,000 and 9,000 yrs BP are more easily mobilized. Climate changes following the last glacial stage increased rainfall and resultant sediment yields, as suggested by a study of pollen fossils [*Igarashi et al.*, 1993].

In scars and deposition zones of DCL where we identified Ta-d layers, Ta-c was mixed with mineral soil at the depth of 30-50 cm from the surface. Additionally, volcanic glass analysis of Ta-d samples in DCL Nos. 3 and 10 showed that refractive indexes of volcanic glass were similar between the Ta-d at the reference site and that of Ta-d in DCL No. 3. Ta-d samples from reference slope A (near the Chiroro River) contained the characteristics of both Ta-d (refractive index 1.530–1.535) and Ta-c (refractive index 1.505–1.510) (**Fig. 3**). This result suggested that the Ta-d layer of DCL No. 3 was pure and stable after the fallout even though it had been on a hillslope. In contrast, the tephra layer of reference slope A was mixed with Ta-c, potentially due to subsequent soil movement after the deposition of Ta-c. Therefore, we considered that the mixture of tephra by subsequent soil movement may have also occurred on the slope of DCL. Ta-d in DCL No. 10 was hydrated, indicating the weathering of tephra after deposition.

DCL No. 2 had Ta-c with the mixture of colluvium materials at 40–50 cm in depth. Therefore, sediment movement was associated the mixture of Ta-c with the other materials. At this scar, Ta-a and Ko-c2 were also found in the surface soil (**Table 1**), and we concluded that the DCL scar was formed 9,000–2,500 yrs ago.

DCL No. 7 did not have any tephra in soil matrix. We identified that DCL No. 7 was likely formed after Ta-a fallout in A.D. 1739. Indeed, because several check dams were installed for debris flow control in the drainage basin of DCL No. 7, sediment movement may be still active due to the sediment supply that occurred more recently, after A.D. 1739.

6. SUMMARY

Our research identified nine DCL features and three occurrence ages including more than 9,000 yrs ago, more than 2,500 yrs ago, and since A.D. 1739 using tephrochronology. Volcanic glass collected in the DCL scars was confirmed to be either pure tephra layers or mixed layers due to subsequent soil movement. Therefore, the ages of occurrence of DCL can be identified using our methods when multiple index tephra are present in a given area. We summarize the procedure for identifying the ages of DCL in the following way. (1) The topography of DCL with concave scars and deposition zones of a fan-shape were identified using the most recent aerial photography and LiDAR data if it was available. (2) Knick lines and other topographic features were investigated using LiDAR data. (3) Topographic parameters were measured using GIS. (4) Scars and deposition were confirmed based on field surveys. (5) Soil was excavated to 1 m to 2 m in depth, and indices of tephra were identified. (6) When identification of tephra was uncertain, tephra samples were collected for the analysis of volcanic glass. Finally, (7) the ages of the formation of DCL scars and deposition were identified based on the results from the field survey and volcanic glass analysis using the following approach. Based on the existence of index tephra, the age of the formation of DCL was considered to be before the eruption age of the oldest tephra among the tephra identified in DCL scars and deposits. Mixed tephra and soil layer may have become mixed due to subsequent soil movement such as shallow landslides within DCL scars and deposits.

These methods can be applied in other areas of Japan that have high a potential for DCL, such as south of the Kyushu and Northern Kanto regions. Thus, we have developed a more comprehensive method for investigating the magnitude and frequency of DCL.

ACKNOWLEDGMENT: This study was supported by “developing methods for identifying potential susceptible slopes and standard of evacuation for deep catastrophic landslides” funded by the Ministry of Land, Infrastructure, Transport and Tourism. We thank the National Institute for Land and Infrastructure Management for providing LiDAR data of the study site.

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