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Hummock alignment in Japanese volcanic debris avalanches controlled by pre-avalanche slope of depositional area

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ABSTRACT

This paper investigates the relationship of hummock orientation to the flow dynamics of volcanic debris avalanches. There are opposing views on whether hummocks are systematically aligned along debris avalanche paths, or not. To investigate this geomorphologically fundamental question, I investigated hummock orientation for six Japanese debris avalanches of two simple styles: four "freely spreading" debris avalanches, and two "valley-filling" debris avalanches. Quantitative GIS-based data analysis revealed that hummock orientation along the avalanche flow path alternated between dominantly parallel to and dominantly perpendicular to the flow direction. These changes of alignment reflect dynamic changes of the local stress field within the avalanche, alternating between extensional and compressional in response to changes of the slope of the pre-avalanche ground surface. Changes of hummock alignment from perpendicular to parallel indicate that the local stress regime has changed from compressional to extensional. Conversely, changes of hummock alignment from parallel to perpendicular indicate that the local stress regime has changed from extensional to compressional. Thus, this research demonstrated a clear relationship between hummock orientation and dynamic changes of stress regime within avalanches that are related to changes of the slope of the pre-avalanche ground surface.

1. Introduction

Volcanoes sometimes collapse, causing catastrophic rockslide-debris avalanches (Siebert, 1992; Ui et al., 2000) that form hummocky terrains (Siebert, 1984). Morphometric analyses of hummocks formed during such avalanches provide insights into past sector collapse events. Results of previous research into the alignment of hummocks with respect to the direction of avalanche flow differ. Early studies reported that hummocks tend to align either parallel with or perpendicular to the flow direction (e.g., Mizuno, 1958). In the past, avalanche flow direction has been estimated on the basis of the orientation of the long axes of hummocks. On the other hand, Ui et al. (2000) suggested that there is no consistent trend of hummock orientation, with a few exceptions where hummocks are aligned parallel to avalanche flow direction.

Most early studies were based on visual evaluations of hummock alignment; there have been few quantitative analyses. Even though more recent studies have taken a quantitative approach (Hoshino et al., 1995; Ikeda and Oyagi, 1996; Sango et al., 1998; Yoshida and Sugai, 2006; Koarai et al., 2008; Shea and van Wyk de Vries, 2008), most of them provide only brief descriptions that suggest a relationship of hummock alignment to flow direction. Although some detailed studies of the mechanisms of formation of hummocky topography provide quantitative data on hummock orientation (Glicken, 1996; Clavero et al., 2002; Dufresne and Davies, 2009; Paguican et al., 2012a), more data are needed to better understand the relationship of hummock orientation to avalanche flow direction. Topographical characteristics of hummocks may provide new geomorphological insights into hummock formation. In particular, examination of simple cases for which the direction of avalanche flow can be determined by other criteria will be useful.

Yoshida and Sugai (2010) investigated the elongation of hummocks of the Zenkoji debris avalanche at Usu volcano in Japan, a topographically simple case where the avalanche spread from the source volcano across a low-relief coastal plain. The results of their study may be key to understanding debris avalanches at Usu volcano, and other similar cases. There are many comparable volcanoes for which hummocky terrains have not been examined in detail, especially in Japan. Studies of these may help to elucidate more decisively the formation of hummocky landforms. It is possible that hummock alignment is dependent in part on avalanche mobility. The possibility that topography along avalanche paths affects hummock alignment was qualitatively examined by Yoshida and Sugai (2010). In this paper, I examine further the relationship of hummock alignment to underlying topography for selected Japanese debris avalanches, based mainly on a geomorphometric approach more comprehensive than previous studies.

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2. Descriptions of debris avalanches studied

2.1. Selection of six avalanches for this study

Previous studies of the size–distance relationship of hummocks for 10 debris avalanches in Japan and one in the Philippines demonstrated that hummock size decreases with distance from the source (Yoshida, 2012a,b; Yoshida et al., 2012; Yoshida, 2013a,b). In these studies, the plan area of each hummock represents the size of each hummock. Although a plan view indicates only one aspect of hummock dimensions because they have three-dimensional extent, such easily-acquired parameter from aerial photos and topographical maps are effective for obtaining many samples. Among the above cases, all but one of the 10 Japanese avalanches (the Kannongawa avalanche; Yoshida, 2012b) were freely spreading avalanches. Even though detailed geological and geo-mechanical studies have not been conducted for some cases, they are considered as typical debris avalanches. Three of the above 10 Japanese avalanches were selected for this study: the Rusutsu debris avalanche at Shiribetsu volcano, the Tokoshinai debris avalanche at Iwaki volcano, and the valley-filling Kannongawa debris avalanche, Nasu Volcanic Group (Fig. 1). These avalanches were selected because their hummocks were clearly identified by the author during stereoscopic interpretation of similar-scale aerial photographs provided by the Geospatial Information Authority of Japan. In addition, the Zenkoji debris avalanche at Usu volcano, previously investigated by Yoshida and Sugai (2010), is investigated in this study.The Yotei debris avalanche at Yotei volcano as a freely spreading one, andthe Toshi lobe of the Kisakata debris avalanche at Chokai volcano as a second representative of a valley-filling avalanche are included (Fig. 1).

2.2. Description of individual debris avalanches

2.2.1. Zenkoji debris avalanche, Usu volcano

Usu volcano in southwestern Hokkaido, Japan (Fig. 1), was formed by repeated eruptions of basaltic and mafic andesitic lava and scoria since the latest Pleistocene (Soya et al., 2007). The pre-existing stratovolcano, after reaching its maximum height of ca. 1000 m above sea level (a.s.l.), suffered a catastrophic sector collapse to form the Zenkoji debris avalanche on its southwestern flank (Fig. 2A). The collapse occurred about 7000 to 8000 years ago according to Soya et al. (2007), but was reported by Fujine et al. (2013) to have occurred at ca. 20 ka during the Last Glacial Maximum. The collapse created an amphitheater with a diameter of 1.8 km, opening to the southwest, leaving the post-collapse summit at 800 m a.s.l. (Fig. 2A). The volume of the avalanche deposit was estimated to be 1–2 km^3 (Takarada and Melendez, 2006). The Zenkoji debris avalanche terminates in the sea (Fig. 2A), with some hummocks forming islands. If the ca. 20 ka age of the debris avalanche (Fujine et al., 2013) is correct, then the hummocks would not have been submerged at the time of their deposition because sea level was then more than 100 m lower than today. The partly submerged hummocks were excluded from this study because their current subaerial orientations and areas may be misleading and because the extent of the offshore distribution of hummocks is unknown. A total of 262 hummocks were included in the analysis of alignment of the Zenkoji avalanche hummocks (Fig. 2A; Yoshida and Sugai, 2010).

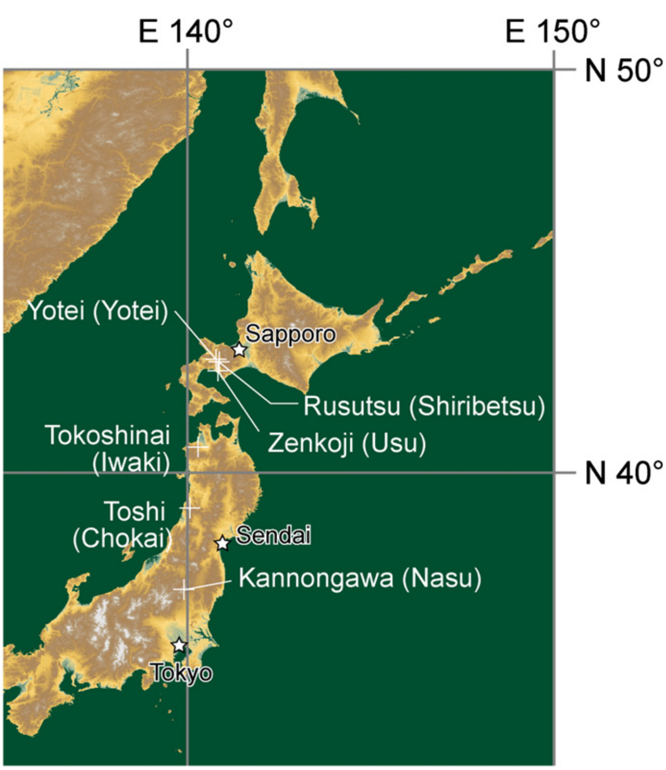

Fig. 1. Map of eastern Japan showing locations of debris avalanches and volcanoes studied.

2.2.2. Rusutsu debris avalanche, Shiribetsu volcano

The Rusutsu rockslide-debris avalanche occurred at Shiribetsu volcano, southwestern Hokkaido (Fig. 1), during the late Pleistocene (Moriya, 2003). The volcano is a small, composite andesitic volcano with its present summit at ca. 1100 m a.s.l. (Fig. 2B). The present topography indicates a ca. 2-km-wide breach of the amphitheater, opening to the west. The shape and size of the avalanche scar indicate a collapse volume of ca. 2 km^3 from a maximum height of 1200–1300 m a.s.l. The distribution of hummocks indicates a horizontal travel distance of ca. 7.5 km from the assumed pre-collapse summit. A total of 172 hummocks were included in my analysis of alignment of the Rusutsu debris avalanche hummocks (Fig. 2B).

2.2.3. Yotei debris avalanche, Yotei volcano

Yotei volcano is northwest of Shiribetsu volcano (Fig. 1). It is a composite stratovolcano of similar size to Iwaki volcano (see Section 2.2.4), with a present summit at ca. 1900 m a.s.l. (Fig. 2C). The Yotei debris avalanche deposit represents a late Pleistocene collapse on the western side of the volcano (Egusa and Nakagawa, 2001). However, mineralogical data indicate that the source area of the Yotei avalanche has since been covered by younger ejecta that form the present conical edifice of the volcano (Egusa and Nakagawa, 2001; Egusa et al., 2003). Consequently, it is difficult to identify the pre-collapse summit, although it was probably near the present summit. I assumed that the source of the Yotei avalanche was at the center of the present crater. The Yotei debris avalanche flowed down the western flank of the volcano to form a hummocky field whose distal area is ca. 120 m a.s.l. (Fig. 2C). Because the avalanche scar is no longer exposed, the collapse volume is unknown. However, the extent of the hummocky field suggests it would have been more than 1 km^3. A total of 297 hummocks were included in my analysis of the Yotei debris avalanche.

2.2.4. Tokoshinai debris avalanche, Iwaki volcano

The Tokoshinai debris avalanche was generated by sector collapse of Iwaki volcano in the northern Tohoku region of Honshu Island, Japan (Fig. 1). The volcano is conical with its summit at ca. 1600 m a.s.l. (Fig. 2D), and is composed mainly of alternating andesitic lava flows and pyroclastic deposits. There are several huge rockslide-debris avalanche deposits of various ages distributed around the foot of the volcano, including the Tokoshinai debris avalanche (Hashimoto et al., 1979; Mimura and Kanaya, 2001), which occurred in the middle Pleistocene (Mimura and Kanaya, 2001). The collapse volume was 1.3 km^3 (Isshiki and Ozawa, 1967), which is similar to that of the Zenkoji debris avalanche. Because the collapse scar of the Tokoshinai debris avalanche has not been preserved, I assumed that the pre-collapse summit was at the same position and altitude as the present summit, giving a runout