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VOLCANIC DRY AVALANCHE DEPOSITS — IDENTIFICATION AND COMPARISON WITH NONVOLCANIC DEBRIS STREAM DEPOSITS

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ABSTRACT

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A "volcanic dry avalanche deposit" is defined as a volcaniclastic deposit formed as a result of a large-scale sector collapse of a volcanic cone associated with some form of volcanic activity. Avalanche transport occurred in response to the gravitational field, in a manner similar to the transport of nonvolcanic debris streams (e.g. Hsü, 1975). Such deposits are characterized by megablock structure — deformed and fractured large blocks up to several hundreds meters in diameter. A megablock preserves original layering, intrusive contacts or weathered surfaces of the source volcanic edifice. Surface topography of the deposit is characterised with hummocky relief. Ratios of fell height to travel distance for volcanic dry avalanche deposits are between 0.18 and 0.06. This range is similar but smaller than the value of 0.58 to 0.08 for nonvolcanic debris stream deposit. This similarity suggests similar transportation mechanisms. Excessive travel distances as defined by Hsü (1975), calculated for volcanic dry avalanche deposits, give values larger than for debris stream deposits of the same volume. The difference is explained by lower rigidity of the collapsing mass due to the existence of soft pyroclastic layers, alteration around the vent, development of fractures owing to new cryptodome intrusion, and boiling of supercritical fluid contained within the collapsed mass.

INTRODUCTION

A "volcanic dry avalanche deposit" is defined as a volcaniclastic deposit formed as a result of large-scale sector collapse of a volcanic cone associated with some form of volcanic activity. The term "volcanic dry avalanche" was first introduced in literature by Nakamura (1978). This type of volcaniclastic deposit has often been described in the past as a mud flow deposit, lahar or volcanic detritus. According to the classification of volcanic eruptions proposed by Macdonald (1972), an ultravulcanian eruption consists of the weak to violent ejection of solid fragments of old rocks. The 1888 eruption of Bandai-san — a historic example of a volcanic dry avalanche — was included within this category. According to Macdonald (1972), no juvenile magma is ejected during an eruption of this type. But in the March 1956 eruption of Bezymianny, Gorshkov (1959) concluded that the summit of the volcano was blown off by a large-scale directed blast, based on eyewitness reports of the eruption column inclined at about 30° to the horizon. According to Williams and McBirney (1979), some of the most powerful eruptions ever recorded were phreatic explosions resulting from the rise of magma into the water-soaked upper part of a volcano, such as the 1955—1956 eruptions of Bezymianny and the 1964 eruption of Shiveluch. They assumed that inclined blasts of immense energy blew out great volumes of lithic debris and were followed by purely magmatic eruptions.

In regard to nonvolcanic debris stream deposits, Heim (1882) explained the mode of transportation for the Elm deposit as follows: starting as a huge rock fall at a sudden steepening of slope the debris stream briefly left the ground, but the energy for motion was transmitted by block-to-block impact. Shreve (1968) later suggested that motion was accomplished at Elm by overriding and compressing a cushion of trapped air, which permitted the debris stream to traverse the gentle slope below with little friction. Howard (1973) insisted that an interstitial fluid, for example, a compressed gas or wet mud, was not necessary for transportation of debris streams in general because of the presence of deposits of a similar type on the lunar surface. Hsü (1975, 1978) reaffirmed Heim's conclusion, and suggested that the dispersion of fine debris and dust among the colliding blocks may have provided an uplifting stress during flowage, adopting the grain flow model proposed by Bagnold (1954). Thus, the energy for transportation of nonvolcanic debris streams is explained as gravitational.

A volcanic dry avalanche deposit was formed at the climactic May 18 eruption of Mount St. Helens in 1980. Observations of bulging prior to sliding and geological surveying of the deposit provides much information concerning the mode of eruption, transportation and deposition of the volcanic dry avalanche deposit (Christiansen, 1980; Lipman and Mullineaux, 1981). Vulcanian-type explosion column or a directed blast was not associated with the initiation of the dry avalanche. Instead, simple gravitational sliding was triggered by an earthquake, as suggested by eyewitness observation (Stoffel and Stoffel, 1980). Thus, the mode of transportation of volcanic dry avalanches is basically the same as that for debris streams.

For purpose of this paper, debris stream deposits are here termed as "nonvolcanic dry avalanche deposits". First, major criteria for the identification of volcanic dry avalanche deposits are given, and then the similarity of apparent coefficients of friction for volcanic and nonvolcanic dry avalanche deposits is discussed.

IDENTIFICATION OF VOLCANIC DRY AVALANCHE DEPOSIT

Several structural and topographical characteristics are commonly observed in volcanic dry avalanche deposits. Their source areas are characterised by collapsed topography, with a wide opening to one side of the former cones. The opening slope developes towards the flank of the volcano, where avalanche material was deposited. In places, large-scale radial grooves developed along this slope. The wide opening containing such collapsed topography, and its enclosing wall, is named as amphitheater (Voight et al., 1981). Usually, a young volcanic cone or dome arises from the floor of amphitheater. For example, a twin dome, 260 m in height, was grown until October 1956 in Bezymianny (Gorshkov, 1959). The amphitheater of the Chokai volcano, Japan, is now partially filled with younger lavas and pyroclastics, 2600 years after the formation of the Kisakata dry avalanche (Kato, 1978). At Yatsugatake volcano, Japan, the amphitheater is completely buried below younger cones (Kawachi, 1977).

A hummocky surface (the conical hills of Williams and McBirney, 1979) is a typical topographic feature of volcanic dry avalanche deposits (Fig. 1). In case of the 1980 deposit at Mount St. Helens, local channelling and

Fig. 1. Hummocky surface of the Kisakata dry avalanche deposit, Kamisaka, northern foot of the Chokai volcano. The area behind the car has been almost left intact by surface erosion. Source of the flow is to the right-hand side. Radiocarbon age of the deposit is ca. 2600 years before present (Kato, 1978).

slumping started just after deposition, and a flat surface made of secondary mud flow and water-laid deposits has developed, but thousands of hummocks protrude above the mean surface elevation of the deposit. Hummocks surrounded by a flat planar surface is a common topographic feature in various older deposits. The flat surface separating individual hummocks might be an effect of long-range reworking, infilling of water-laid sediments, and development of vegitation cover. Secondary water-influenced portions of a volcanic dry avalanche deposit consist of a mixture various kinds and sizes of rock fragments, with common sorting and grading effects. This part of a volcanic dry avalanche deposit is hard to distinguish from simple water-laid volcaniclastic deposits.

Each hummock consists of one or a few megablocks (Fig. 2). A megablock consists of a former portion of the volcanic edifice, transported to present site by dry avalanche (Mimura and Kawachi, 1981). The interior of a megablock is fractured into numerous clasts (Fig. 3). Adjacent clasts within part of megablock often show identical lithologic character, and outlines of nearby clasts occasionally fit each other, for example Pankechin dry avalanche, Shikaribetsu volcano (Yamagishi, 1977). It is sometimes possible to reconstruct the form of primary igneous body prior

Fig. 2. An example of megablock structure in the Nirasaki dry avalanche deposit. A section of hummocky hill at Anayamabashi, Yatsugatake volcano. Alteration of lavas and pyroclastics, dipping right-hand side is slightly deformed and displaced due to fracturing and minor normal faulting.

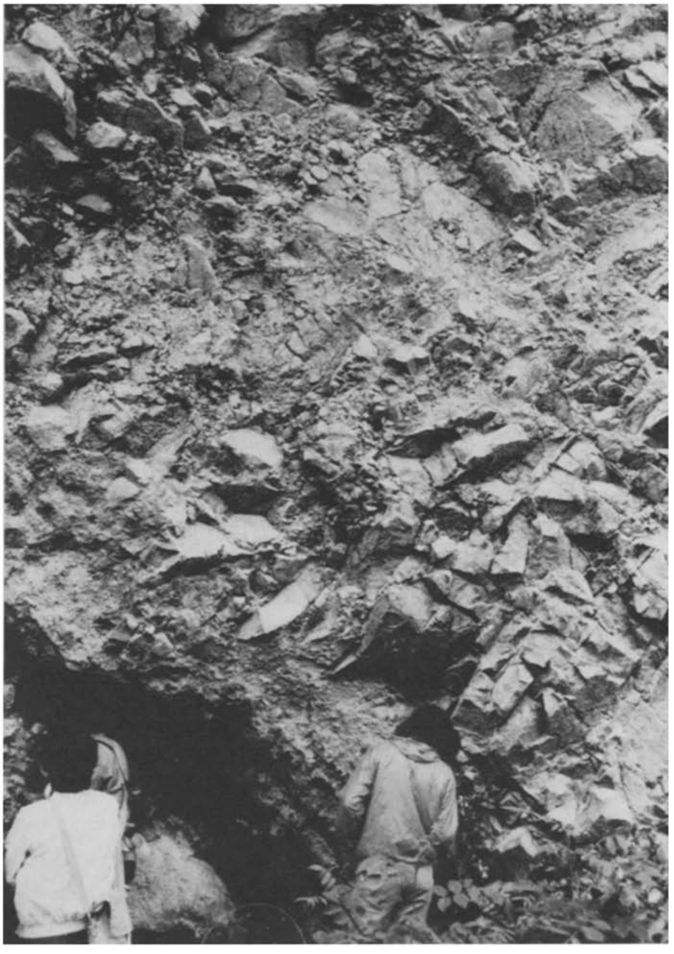

Fig. 3. Fracturing of lava flow within a megablock. Kamanashi-gawa-bashi, Nirasaki dry avalanche deposit, Yatsugatake volcano. Lower left corner is the base of a lava flow, dipping towards right. Irregular fractures are abundant within massive part of the lava flow. Cooling joint plane is observable at upper right.

to fracturing, if rotations and transformations can be deduced in three dimensions for each clast. Thus megablocks can be judged in relation to originally massive parts of lava flows or intrusives. Lithologic facies boundaries occur as contacts of air-fall tuffs and lavas, intrusion contacts, or weathered surfaces. Such boundaries are usually disturbed by fracturing. Shreve (1968) described similar fractured boundaries in the Blackhawk nonvolcanic dry avalanche deposit, and named it the jigsaw puzzle effect.

Mimura et al. (1971) showed by natural remanent magnetization measurements of the late-Quaternary Nirasaki dry avalanche deposit at Yatsugatake volcano that the inclination and declination of various clasts within a megablock show similar directions, but that declinations are variable among nearby megablocks. Inclination of all measured megablocks in the deposit shows a direction similar to that of the present magnetic field of the earth. Thus the megablocks were transported to their present sites at the foot of a volcano without appreciable rolling.

The average size of megablocks is variable among the various deposits, and variation in size is considerable even within a single deposit. The maximum size recorded is 500 m in diameter, in the Nirasaki dry avalanche deposit of Yatsugatake volcano (Mimura and Kawachi, 1981). An abrupt change of internal structure associated with the change of degree of fracturing or of lithologic character defines the boundary of adjacent megablocks. Sometimes, adjacent megablocks show evidence of accretion, separated by a flattened layer of soil or tuff, a few meters in thickness (equivalent to "soil schlieren" of Shreve, 1968). Thickness of the layer of separation is variable and depends on the shape of the megablocks.

The size and number of megablocks decreases towards the marginal or distal end of a deposit; the amount of matrix mixture correspondingly increases (Mimura and Kawachi, 1981). The matrix consists of various

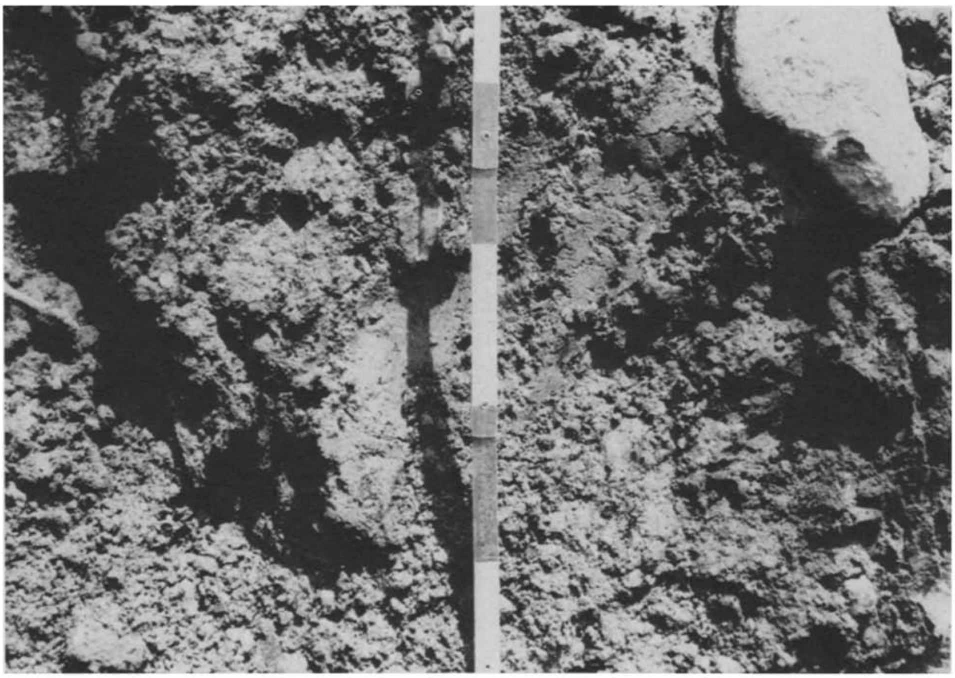

Fig. 4. Matrix of volcanic dry avalanche deposit, Nagaoka, Kisakata dry avalanche deposit, Chokai volcano. Matrix mainly consists of a mixture of finer volcanic clasts; Gravel (upper right), chips of soil (center and left of scale), and fragment of twig (middle left). Small megablocks occur locally but are not visible within this figure. Banded stripe on the scale expresses 10 cm in length.

kinds of rock fragments, finer tuffaceous particles, chips of surface soil scraped off during flowage, alluvial gravels, and fragments of plants (Fig. 4). Megablocks of small size, several tens of centimeters to a few meters in diameter are usually included within the matrix mixture. Levees (lateral deposits) at lateral margins of the deposit are described in the case of the Mount St. Helens deposit (Voight et al., 1981). Similar topographic feature is developed at the northern margin of 1792 volcanic dry avalanche deposit of Unzen volcano. Interior of the levee shows similar structure to the matrix mixture.

APPARENT COEFFICIENT OF FRICTION FOR VOLCANIC DRY AVALANCHE DEPOSIT

Based on the criteria just described, I have searched for volcanic dry avalanche deposits in the literature descriptions of various volcanoes. Results of this search are listed in Table I. I have also made field observations at some of these deposits in order to verify the mode of emplacement as volcanic dry avalanches. Field-verified deposits are marked with asterisks in Table I. The inferred highest altitude of the source region and the lowest altitude of a deposit were located from topographic and published geologic maps, or by direct field work. The difference between high and low elevations define the maximum height difference during transportation (*H*). Maximum travel distance (*L*) was similarly determined. Volume (*V*) of the deposit was estimated from direct field data or from published geologic descriptions. *L*, *H* and *V* for nonvolcanic dry avalanche deposits (Hsü, 1975) and for nuée ardente deposits are listed in Tables II and III for comparison, and the relationships between *H* and *L* are plotted on Fig. 5.

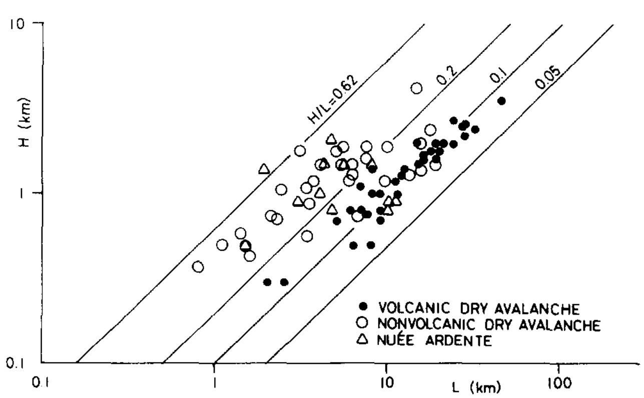

Fig. 5. Relationship between maximum fall height (*H*) and maximum travel distance (*L*). Data are listed in Tables I, II and III. The average *H/L* ratio for volcanic dry avalanche deposits are smaller than those for nonvolcanic dry avalanche deposits.

TABLE I

Volcanic dry avalanche deposits

Name of volcano	Name of deposit	H(km)	L(km)	H/L	L_e(km)	V(km^3)	Data source
16 Imuta		* 0.3	2	0.15	1.5		T. Kobayashi, pers. commun., 1982
18 Unzen	1792 Maeyama	* 0.7	6	0.12	3.9	0.48	Katayama, 1974
62 Fuji	Kofuji	2	24	0.083	21		Tsuya, 1940
64 Yatsugatake	Nirasaki	* 2.4	32	0.075	28	9.0	Mimura and Kawachi, 1981
64 Yatsugatake	Otsukigawa	1.4	12.5	0.112	10.2	0.27	Kawachi, 1981
77 Tomuro		* 0.3	2.5	0.12	2.0		Imai, 1959
85 Myoko	Sekikawa	2.0	19	0.105	16	0.8±0.2	Hayatsu, 1976
85 Myoko	Taguchi	1.4	8	0.175	5.7	0.23	Hayatsu, 1976
85 Myoko	Yashirogawa	1.8	18	0.1	15		Hayatsu, 1976
86 Kurohime	Nabewarigawa	0.8	6	0.133	4.7	0.12	Hayatsu, 1976
87 Iizuna		0.8	6	0.133	4.7		Hayatsu, 1976
91 Asama	Tsukahara	* 1.8	20	0.09	17	2	Aramaki, 1963
91 Asama	Okuwa	* 1.6	16	0.1	13		Aramaki, 1963
104 Akagi	Nashikizawa	1.6	19	0.084	16	4	Moriya, 1968
114 Nasu		* 1.6	19	0.084	16		Kato, 1964
120 Bandai-san	1888	* 1.2	11	0.109	9.1	1.5	Nakamura, 1978
120 Bandai-san	Okinajima	* 1.5	15	0.1	13		Mizuno, 1958
127 Shirataka		* 0.5	8	0.063	7.2		Ui and Shibahashi, in press
129 Gassan	Sasagawa	* 1.95	21	0.093	18		Ichimura, 1955; Ui, 1975
— Hayama	Hata	1.0	8	0.125	6.4		Ui and Shibahashi, in press

135 Chokai	Kisakata	* 0.2	25	0.088	21		Kato, 1978
142 Iwate	Gohyakumori	* 1.7	16	0.106	13		Tachibana, 1978
151 Tashiro	Itazawa	* 0.7	9	0.078	7.9		Sumi et al., 1962
153 Iwaki		1.5	15	0.1	13	1.3	Isshiki and Ozawa, 1967
187 Komagatake	Kurumizawa	1.0	11.5	0.087	9.9	0.25	Katsui et al., 1975
187 Komagatake	Bateikei-kako	1.0	9	0.111	7.4		Katsui et al., 1975
193 Usu	Zenkoji	* 0.5	6.5	0.077	5.7	0.3	Oba, 1966
194 Yotei		1.6	9.0	0.178	6.4		I. Moriya, pers. commun., 1982
— Shiribetsu		0.75	7.5	0.1	6.3		I. Moriya, pers. commun., 1982
216 Shikaribetsu	Eishin	* 0.8	7	0.114	5.7		Yamagishi, 1977
216 Shikaribetsu	Pankechin	* 0.8	9	0.089	7.7		Yamagishi, 1977
Kharimkotan		1.1	7	0.16	5.2		Gorshkov and Dubik, 1970
Bezymianny	1956	2.2	28	0.079	24	1.0	Gorshkov, 1959
Shiveluch	1964	2	15	0.13	12	1.5	Gorshkov and Dubik, 1970
St. Helens	1980	* 2.6	28	0.093	24	2.5±0.5	Voight et al., 1981
Shasta		3.5	45	0.078	39		
Mombacho		* 1.3	12	0.108	9.9	1	Ui, 1972a
Parinacota	Cotacotani I	* 2.0	19	0.105	16		Katsui and Gonzalez, 1968
White Island	1914	0.06	1	0.06	0.9		Cotton, 1944
Ruapehu		1.7	16	0.106	13		Grange, 1931
Egmont	Pungarehu	2.5	27	0.093	23	6	Grange, 1931
Galunggung	1822	1.8	20	0.09	17		Cotton, 1944
Enta		2.7	24	0.113	20		Tanguy and Kieffer, 1977

Note: Digits given preceding volcano name is reference number in "Volcanoes of Japan" (Ono et al., 1981). H = Collapse height; L = travel distance; L_e = excessive travel distance; V = deposit volume; * = field-verified deposit.

TABLE II

Nonvolcanic dry avalanche deposits (after Hsü, 1975)

Locality	H(km)	L(km)	H/L	L_e(km)	V(km^3)
Schächental	1.8	3.1	0.58	0.2	0.0005
Val Lagone	1.05	2.4	0.44	0.7	0.0005—0.0008
Mombiel	0.37	0.8	0.47	0.2	0.0008
Huascaran	4.2	14.5	0.30	11.8	0.002
Wengen 1	0.5	1.1	0.45	0.3	0.002—0.003
Wengen 2	0.59	1.4	0.42	0.45	0.005—0.006
Elm	0.71	2.3	0.31	1.15	0.01
Disentis	0.74	2.1	0.36	0.9	0.01—0.02
Corno di Dosde	1.2	3.7	0.32	1.8	0.02
Madison	0.43	1.6	0.27	0.9	0.029
Voralpsee	1.1	3.4	0.33	1.6	0.03
Frank	0.87	3.5	0.25	2.1	0.03
Sherman	1.3	6.2	0.21	4.1	0.03
Gordau	1.2	6.0	0.21	4.0	0.03—0.04
Gros Ventre	0.56	3.4	0.17	2.5	0.038
Diablerets	1.9	5.5	0.34	2.5	0.05
Scimada Saoseo	1.5	5.5	0.27	3.1	0.08
Obersee GL	1.8	5.0	0.36	2.1	0.12
Kandeltal	1.9	9.9	0.19	6.9	0.14
Poshivo	1.5	4.1	0.36	1.7	0.15
Vaiont	0.5	1.5	0.34	0.7	0.25
Blackhawk	1.2	9.6	0.13	7.6	0.28
Deyen, Glarus	0.74	6.6	0.11	5.4	0.6
Glarnish	1.9	7.5	0.25	4.5	0.8
Fernpass	1.4	15.6	0.09	13.3	1.0
Siders	2.4	17.4	0.14	13.5	1.0—2.0
Tamins	1.3	13.5	0.095	11.4	1.3
Pamir	1.5	6.2	0.24	3.8	2.0
Engelberg	1.6	7.4	0.22	4.8	2.5—3.0
Flims	2.0	15.6	0.13	12.3	12
Saidmarreh	1.5	18.9	0.08	16.5	20

The H/L ratio, equivalent to the apparent coefficient of friction for volcanic dry avalanche deposits, occurs within the range 0.18 to 0.06. The ratio slightly decreases with increasing H and L. The equivalent range for nonvolcanic dry avalanche deposits is between 0.58 and 0.08, decreasing with increasing H and L (Hsü, 1975). At the higher range of H and L, the ratio seems to be identical for both volcanic and nonvolcanic dry avalanches. Smaller H/L ratios for volcanic and nonvolcanic dry avalanches, compared with the case of sliding of rigid blocks (H/L = 0.62, (Hsü, 1975)), suggests lower rigidity for both kinds of dry avalanches during the process of transportation. The similarity of the H/L ratio for volcanic and nonvolcanic dry avalanches suggests that the mode of transportation of both are basically identical; both are related to gravitational sliding associated with

TABLE III

Nuée ardente deposits

Name of volcano	Name of deposit	H(km)	L(km)	H/L	L_e(km)	V(km^3)	Data source
60 Hakone	Kamiyama	* 0.8	4.7	0.17	3.4		Oki et al., 1978
76 Hakusan		0.5	1.5	0.33	0.7	0.002	Yamasaki et al., 1964
83 Shirouma-Oike	Kazefukidake	1	4	0.25	2.4	0.03	Sakuyama, 1980
91 Asama	Kanbara	* 1.45	8	0.18	5.7	$10^{-2\ -3}$	Aramaki, 1963
135 Chokai	Odaino	* 0.9	10	0.09	8.5	1.0	Ui, 1972b
216 Shikaribetsu	Ogigahara	0.8	1.0	0.08	8.7		Yamagishi, 1977
216 Shikaribetsu	Shinkai	* 0.9	11	0.08	9.5		Yamagishi, 1977
Santiaguito	April 1973	1.5	4.2	0.36	1.8		Rose et al., 1977
Santiaguito	Sept. 1973	0.9	3.0	0.3	1.5	0.002	Rose et al., 1977
Ngauruhoe	1974	1.4	1.9	0.74	0		Sheridan, 1980
Mayon	1968	2.1	4.7	0.45	1.3	0.015	Moore and Melson, 1969
Hibok-Hibok	1951	1.5	5.6	0.27	3.2		Sheridan, 1980

Note: Digits given preceding volcano name are reference numbers in "Volcanoes of Japan" (Ono et al., 1981). H = collapse height; L = travel distance; L_e = excessive travel distance; V = deposit volume; * = field-verified deposit.

slope instability just as observed at Mount St. Helens (Christiansen, 1980; Voight et al., 1981) and in numerous examples of nonvolcanic dry avalanche (Hsü, 1975). Hsü demonstrated that the apparent coefficient of friction for nonvolcanic dry avalanches decreases with increasing volume. A similar trend is obtained for the data of volcanic dry avalanche deposits (Fig. 6).

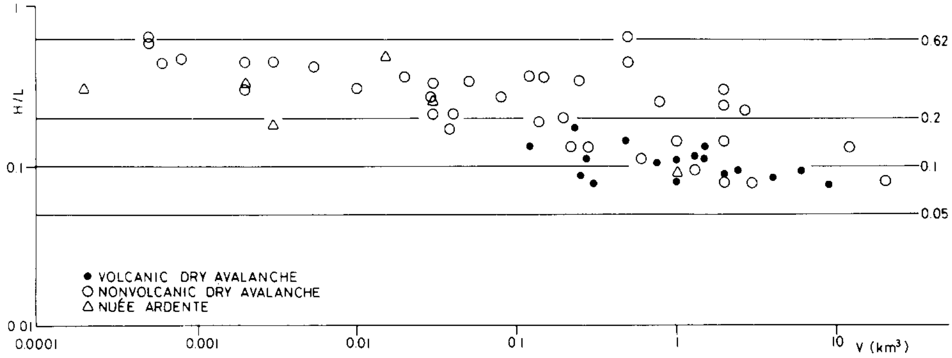

Fig. 6. Relationship between apparent coefficient of friction (H/L) and deposit volume (V). Symbols are identical with Fig. 5. H/L slightly decreases with increasing V.

A parameter called excessive travel distance (L_e) was defined by Hsü (1975) as the travel distance beyond the point obtainable by sliding of a body with an 0.62 friction coefficient. The relation is expressed by:

$$L_e = L - H/0.62$$

Volcanic dry avalanches have a slightly larger excessive travel distance (L_e) compared with nonvolcanic dry avalanches of the same volume range (Fig. 7).

Slightly smaller H/L ratios and slightly larger L_e values for volcanic dry avalanches are explained by the following factors:

(1) A volcanic edifice consists structurally of alternating soft pyroclastic layers, rigid lava flows and welded pyroclastic layers. Parts of the volcanic mass, especially around the vent, have suffered from fumarolic alteration.

(2) Fracturing of solid lava or welded pyroclastic layer (jigsaw puzzle effect) is common in parts of volcanic dry avalanche deposits. In case of Mount St. Helens, fractures are observed both in the dry avalanche deposit and in parts of the amphitheater wall (Voight et al., 1981). Bulging and fracturing of the surface due to an intrusion of a new cryptodome started at least 2 months before the climax eruption (Voight et al., 1981). This evidence suggests that fractures were already growing prior to the initiation of sliding.

(3) Heat discharge from the new cryptodome is helpful in converting

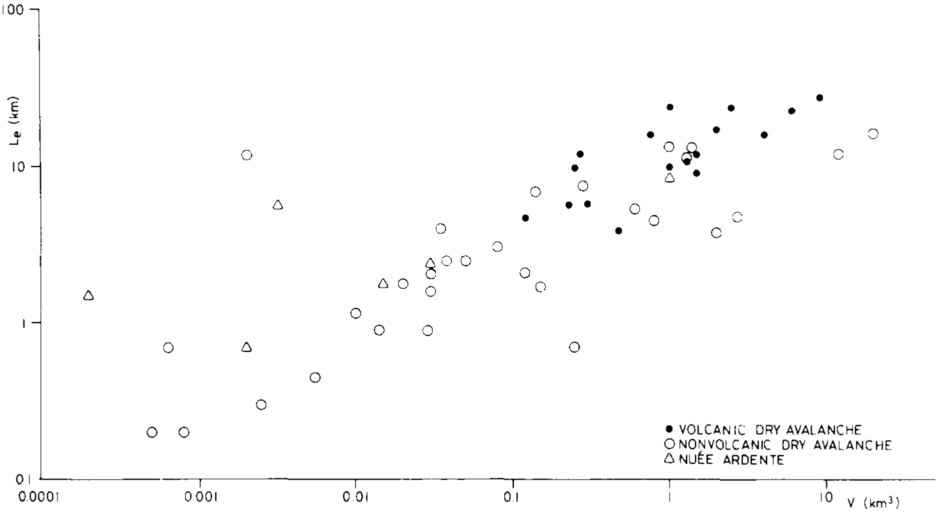

Fig. 7. Relationship between excess travel distance (L_e) and deposit volume (V). Symbols are identical with Fig. 5. L_e increases with increasing V. L_e for volcanic dry avalanche deposits are slightly larger than those for nonvolcanic dry avalanche deposits.

ground water to a supercritical fluid. Many projectiles with steam traillers were emitted from various portions of the sliding mass in the Mount St. Helens slide and consequent eruption. Sudden release of pressure due to initiation of sliding permitted the boiling of supercritical fluid within the volcanic edifice. This produced additional fracturing. A similar event was not documented for other similar historic eruptions, i.e. Bandai-san, Bezymianny and Shiveluch, but nevertheless possibly occurred.

These three factors explain the lower rigidity of the sliding block, the lower apparent coefficient of friction (H/L ratio) and the larger excessive travel distance (L_e) noted for the volcanic dry avalanche deposit.

CONCLUSIONS

Volcanic dry avalanche deposits are characterized by megablocks, jigsaw puzzle effects, hummocky surface, and amphitheater at the source. Similarity of the collapse height (H) to travel distance (L) ratio on volcanic and nonvolcanic dry avalanche (debris stream) deposits suggests the mode of transportation as gravitational sliding. Observations in the May 1980 eruption of Mount St. Helens support this model. The apparent coefficient of friction (H/L) is slightly smaller and the excessive travel distance (L_e) is slightly larger than those of nonvolcanic dry avalanches throughout the entire volume range. These differences are explained by smaller rigidity of the collapsing mass due to soft pyroclastic layers, alteration around the vent, fractures due to an intrusion of a cryptodome, and boiling of supercritical fluid contained within the collapsed mass.

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