Characteristics of large rock avalanches triggered by the November 3, 2002 Denali Fault earthquake, Alaska, USA

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ABSTRACT: Deposits of rock avalanches triggered by the November 3, 2002 Denali Fault, Alaska, USA earthquake (**M** 7.9) with volumes of 4-20 x 10^6 m^3 were examined. The deposits consisted of clay-sized to 20-m-diameter rock fragments and had poorly sorted interiors and coarse tops. Boulders coated with smaller rock fragments, fragile but unbroken boulders, and precariously balanced rocks were common. Open-slope deposits generally had consistent 2-4 m thickness. Channelized deposit thickness varied; these consisted of overlapping deposits of individual waves. Different rock type zones overlapped in the channelized deposits and abutted one another in the open-slope deposits. The open-slope deposits had wrinkles and faults. Substrate overrun by the avalanches was generally undisturbed. Observations suggest that channelized avalanches flowed as succeeding waves and open-slope avalanches flowed as coherent units. The avalanches had semi-rigid upper parts carried by laminar-flowing lower parts, similar to viscoplastic fluids or dispersive granular flows.

1 INRODUCTION

The Denali fault earthquake of November 3, 2002 (**M** 7.9), southeastern Alaska, USA, triggered seven rock slides with volumes greater than 4 x 10^6 m^3 that traveled as far as 11 km. Features of rock-slide deposits indicated that the slides moved as avalanches (large, extremely rapid flows), similar to rock avalanches described previously (e.g., Heim 1932; McSaveney 1978; Davies 1982; Mauthner 1996; Evans and Clague 1998; Strom 1998; Barla et al. 2000). Rock avalanches have created extreme hazards due to their great mobility and energy; single avalanches have killed hundreds to thousands of people and destroyed entire cities (e.g., Heim 1932; Schuster 1996). Thus, rock avalanches have been studied since at least Heim (1932) to gain understanding of their movement characteristics for the purpose of reducing their hazards. Heim (1932) and others after him (e.g., Kent 1965; Hsu 1975; McSaveney 1978) proposed that avalanches move as a fluid, while others have proposed that they may also move as disintegrating blocks of rock (McSaveney 1978) or sliding blocks riding on air cushions (Shreve 1968; Bock 1977). Heim (1932) recognized that avalanche mobility is directly related to avalanche volume and Scheidegger (1973) reinforced this finding with statistical analyses. Fixed rheological models have been proposed to explain avalanche movement (McSaveney 1978) while some have proposed models based primarily on interaction of particles within avalanches and other flowing particulate systems, such as debris flow (e.g., Bagnold 1956; Savage 1979; McTigue 1982; Johnson 1996; Iverson 1997; Iverson and Denlinger 2001). All attempts to explain avalanche characteristics rely on field observations of their deposits or the few observations of avalanches in motion (e.g., Heim 1932). The variety of terrain over which the Denali-earthquake-triggered avalanches moved made them particularly useful for study of avalanche movement characteristics. Presented herein are descriptions of the largest of the Denali-earthquake-triggered avalanche deposits and discussion of potential avalanche movement characteristics. The descriptions are based on field observations made of avalanche deposits during November 2002 and September 2003, mapping in the field and from aerial photographs, and analysis.

2 THE DENALI-EARTHQUAKE-TRIGGERED LARGE AVALANCHES

The seven largest avalanches triggered by the Denali earthquake had volumes of 4-20 x 10^6 m^3 and were produced by rock slides that occurred on mountainsides inclined 26-55°. The Denali avalanches had typical runout lengths for their volumes and fall heights (Jibson et al. 2004, 2006). Three of the avalanches moved down planar (open) slopes inclined 28-35° without leaving significant deposits until reaching the nearly flat surface of a valley glacier where deposits 3.2-4.6 km long and 1.0-1.6 km wide were formed (Fig. 1). The other four avalanches formed from rock slides located at the heads of valley glaciers and left deposits along their entire paths. Two of these avalanches were channelized within 4-12°-inclined glacial valleys along their entire paths and produced deposits 11.0-11.5 km long and 0.7-1.5 km wide (Fig. 2). The remaining two avalanches were channelized initially within 10-12°-inclined hanging glacial valleys before moving down the open wall of the main glacial valley (inclined 26°) and finally onto the flat surface of the main valley glacier (Fig. 3). These avalanches left deposits 3.3-4.1 km long and 0.7-0.8 km wide. There were some characteristics common to all seven of the avalanches, while some characteristics were restricted to certain types of terrain crossed by the avalanches.


Figure 1. Oblique aerial photograph of most of an open-slope avalanche deposit on a glacier. View is in the direction of avalanche movement and is 1,400 m wide.

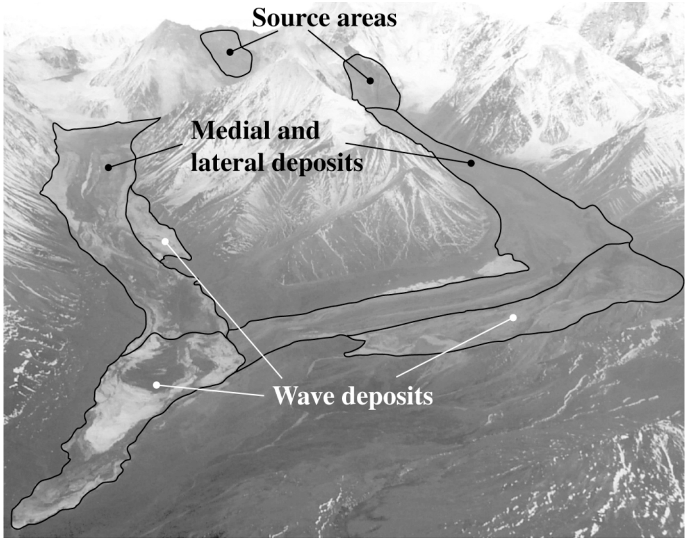

Figure 2. Oblique aerial photograph of deposits of the two avalanches channelized within glacial valleys. Both deposits are about 11 km long and consist of overlapping medial, lateral, and wave deposits.


Figure 3. Oblique aerial photograph of the deposit of an avalanche that was initially channelized then moved over a steep open slope and onto a flat glacier. Deposit width averages about 700 m.

2.1 *Characteristics common to all seven avalanches and their deposits*

All of the avalanches apparently produced overriding dust clouds, similar to other avalanches (e.g., Heim 1932), as indicated by fine-grained deposits that extended hundreds of meters beyond the main avalanche deposits. The main avalanche deposits generally had consistent thicknesses of 2-4 m along their lengths and had abrupt margins inclined about 35° (Fig. 4). From visual inspection, the deposits consisted of subangular to rounded rock fragments that were bounded by fresh (unweathered) surfaces, and as much as 10% glacial ice and snow. Fragments of rock ranged in diameter from clay to boulder size, including boulders as large as 20 m in diameter. The outer surfaces of the deposits displayed concentrations of about 80% cobbles through boulders and 20% pebbles through clay. Prior to our September 2003 field evaluation, deposit interiors were exposed by sloughing of deposit margins caused by ablation of glacial ice adjacent to most of the deposits (Fig. 5). From these exposures, the lower two-thirds of deposits appeared to have about equal amounts of cobbles through boulders and pebbles through clay, and the upper one-third consisted mostly of the coarser fraction (Fig. 5). Rock-fragment size distributions appeared consistent with distance from source areas; changes in these distributions occurred across abrupt boundaries that correlated with rock type changes. Exceptionally large boulders were scattered throughout the deposits in apparent random locations (Figs. 1 and 3-5). These boulders were frequently observed to be resting on underlying deposit, rather than on the substrate (Fig. 5).

The upper surfaces of many boulders were covered with finer rock fragments and many of these boulders were located adjacent to boulders that were free of this covering (Figs. 5 and 6). Boulders as large as 20 m were observed covered by 2-m boulders and finer fragments. The distribution of coated and uncoated boulders was consistent along the length of the deposits, including along deposit margins. Cobbles and boulders balanced precariously on others were similarly distributed.

Figure 4. Oblique aerial photograph taken 10 months after deposit formation of an avalanche deposit on a glacier. Avalanche moved from right to left. Length of near side of deposit in view is about 380 m. Dashed line delineates base of deposit; material below line is ice covered by sloughed deposit resulting from ablation of adjacent ice. Deposit formed on a medial moraine in left side of view. Deposit is 2 m thick on the glacier, 3 m thick on right side of medial moraine, and 1-1.5 m thick on left side of medial moraine.

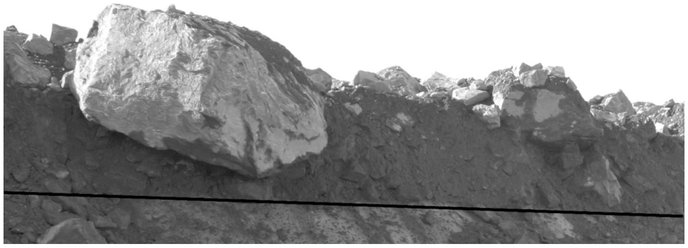

Figure 5. Photograph taken 10 months after deposit formation of a vertical exposure of an avalanche deposit. Exposure was created by ablation of adjacent glacial ice. Deposit averages about 2 m thick. Black line delineates base of deposit; glacial ice covered by sloughed deposit is below the line.

Figure 6. Photograph of large boulders both coated and uncoated by finer material. Note geologist (circled) for scale. Photograph was taken near the distal end of the deposit shown in Figure 3.

Boulders in various stages of mechanical breakdown were observed throughout most of the deposits during September 2003, but not during November 2002. Degree of breakdown ranged from rocks that were cut by through-going fractures but remained together like a completed jigsaw puzzle, to conical piles of rock fragments with “jigsaw”-boulder cores.

Along about 80% of their margins, the deposits rested on apparently undisturbed substrate (ice and soil covered by low grasses, lichen, sedge, etc.). Along about 20% of deposit margins, substrate was buckled, folded, plowed, or stripped and resting on the deposits. In a few locations, avalanches overran soil and vegetation and formed discontinuous deposits; overrun soil and vegetation generally appeared to be undisturbed (Fig. 7). Based on heights of overrun ridges and super-elevation through channel bends, we calculated estimated avalanche velocities greater than 50 m/s for some of these undisturbed overrun areas (Jibson et al. 2004, 2006).

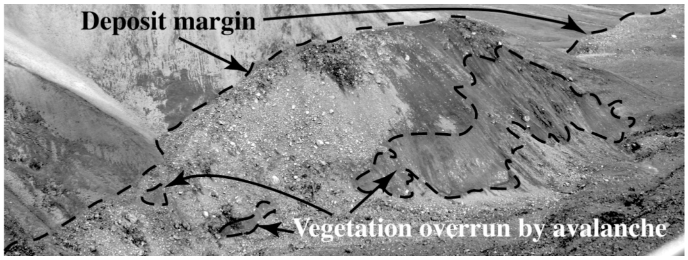

Figure 7. Oblique aerial photograph of a 150-m-high ridge overrun by an avalanche. Avalanche movement was from lower left to upper right. Note vegetation visible through the discontinuous avalanche deposit.

2.2 *Characteristics common to the deposits of open-slope avalanches*

Planar, or open slopes down which five of the avalanches moved were either steep (26-35°) valley walls or flat (0-2°) glacier surfaces. Only two of the avalanches created significant deposits on the steep open slopes; these were the avalanches channelized initially within hanging glacial valleys (Fig. 3). These deposits were 2-6 m high lateral deposits and discontinuous, 1-2 m thick medial deposits (as described by Johnson 1970). All five open-slope avalanches formed similar deposits on the flat surfaces of glaciers (Figs. 1, 3, 4, and 8). These deposits were roughly semicircular in plan and of generally consistent thickness of 2-4 m. Thickness was so consistent that less than meter wide, apparent glacial crevasses (based on projection of crevasses exposed adjacent to the deposits) resulted in linear depressions in the deposits. Deposit thickness varied where three of the avalanches crossed a 50-m-high medial moraine with 35° side slopes; deposits were thicker on the proximal side (nearest the source area) of the moraine and thinner on the distal side (opposite the source area) than on the flat glacier (Fig. 4). Thickness also varied on the proximal side of obstacles, such as the medial moraine, and near the foot of the source mountainsides where curvilinear ridges oriented normal to the direction of avalanche movement were observed. These ridges were generally about twice as high as the deposits were thick and had the appearance of wrinkles (Figs. 8 and 9).

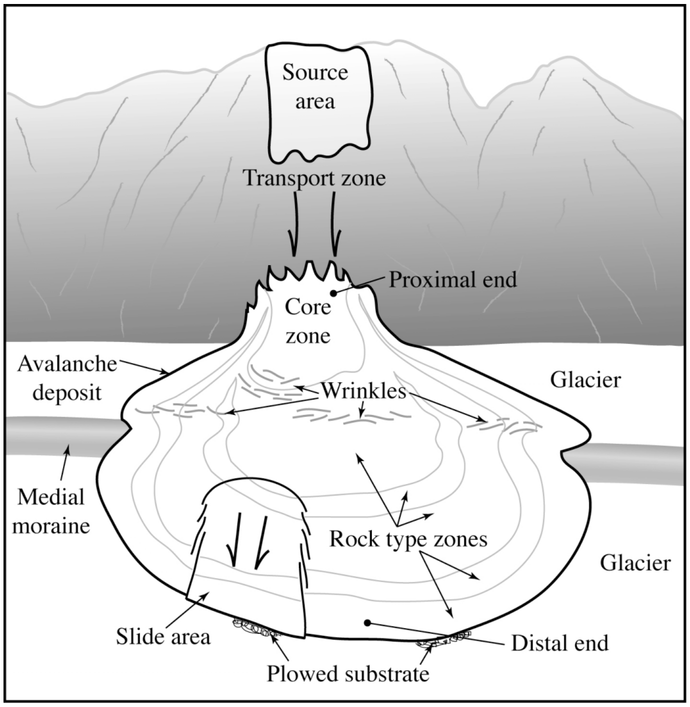

Figure 8. Oblique cartoon view of an idealized avalanche deposit on a glacier. View is from opposite side of glacial valley; avalanche moved toward viewer. Deposit covers a medial moraine and has wrinkles, rock type zones, and a slide area. Glacial ice (substrate) was locally plowed by the avalanche.

The open-slope deposits on the flat glaciers had zones of different rock type. Generally, one zone formed a core of each deposit, in plan, located at the center of the proximal end of the deposit (Fig. 1, core zone in right center, Fig. 8). Additional zones radiated out from the core in subparallel bands such that each zone comprised a band located at a consistent distance from the deposit margin and core zone(s). The largest three of the open-slope deposits on flat glaciers were cut by apparent faults across which the zones were offset (Figs. 8 and 10). Most of these faults were hundreds of meters long and oriented subparallel to deposit margins, some were tens-of-meters-long, apparent en echelon fractures, and some were arcuate, oriented concave to deposit distal ends, and transected nearly the entire width of the deposits. Fault and offsets were arranged such that the central areas of the distal parts of the avalanches moved farther than the surrounding avalanche material (Fig. 8).

2.3 *Characteristics common to the deposits of channelized avalanches*

Dust-cloud deposits extended highest up valley walls near the avalanche source areas and up to consistent, lower heights beyond the source areas above the main deposits of the entirely channelized avalanches. The main deposits of the channelized avalanches (Figs. 2, 11, and 12) consisted of overlapping medial, lateral, and wave deposits (Johnson 1970). Medial deposits are the thinnest of the three types and form along most of the path of an avalanche. Lateral deposits are ridge-like deposits located along most of the sides of medial deposits and are thicker than medial deposits. Wave deposits are found at the distal ends of medial deposits, are the thickest of the three deposit types, and usually are convex in longitudinal and transverse profile. The overlapping nature of the channelized deposits resulted in total deposit thicknesses of 1-10 m; individual medial, lateral, and wave deposits were typically 0.5-2, 1-3, and 2-5 m thick, respectively, and nearly as wide as the entire deposits. These overlapping deposits were occasionally of different rock type so formed linear compositional zones hundreds to thousands of meters long.

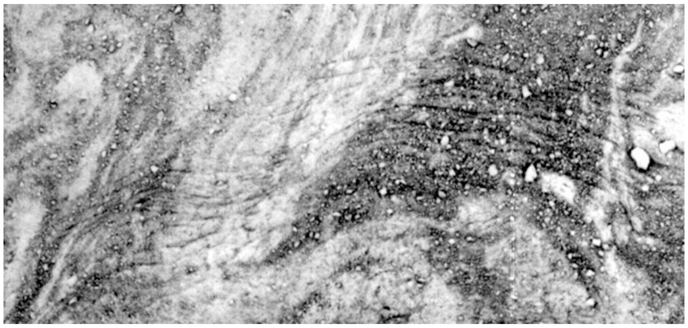

Figure 9. Vertical aerial photograph of apparent wrinkles in an open-slope avalanche deposit. View is 225 m wide. Avalanche movement was from the lower part of the view to the upper part of the view.

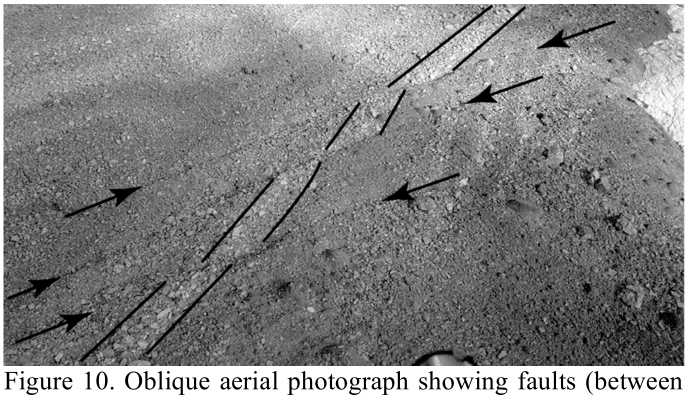

Figure 10. Oblique aerial photograph showing faults (between arrows) offsetting rock type zones near the distal end (right side) of an open-slope avalanche deposit. One compositional band is outlined to illustrate the offset. Avalanche movement was from lower left to upper right and central part of deposit is toward upper left. Center of view is about 350 m wide.

3 DISCUSSION

Characteristics of the Denali avalanche deposits permit inferences to be made regarding characteristics of the avalanches. The avalanche deposits indicated that the avalanches flowed; deposits covered areas many times larger than the sizes of source areas, filled channels, had consistent thicknesses, laterally extensive compositional zones, and lateral, medial, and wave deposits, similar to debris flows and pyroclastic flows (e.g., Johnson 1970; Hsü 1975; Hoblitt 1986). Movement characteristics of the avalanches appeared to be consistent beyond the foot of source mountainsides as indicated by the consistency of deposit morphology. However, the avalanches first were transformed from the rock slides triggered by the earthquake.

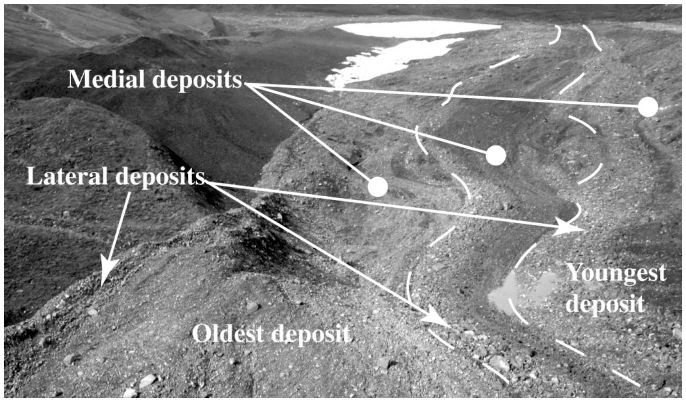

Figure 11. Oblique aerial photograph of overlapping channelized avalanche deposits. View is in opposite direction of avalanche movement and shows a side of the overall deposit. Three overlapped deposits are highlighted. Each overlapped deposit includes lateral and medial deposits. Lower part of the view is about 350 m wide.

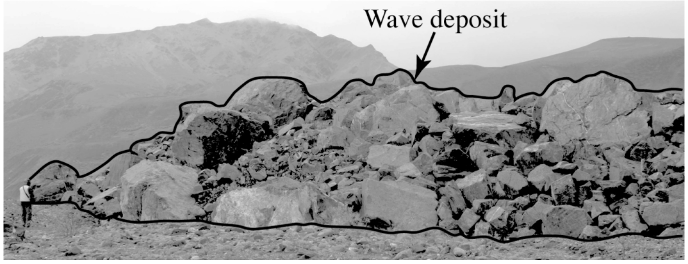

Figure 12. Photograph of a wave deposit at the distal end of a channelized avalanche deposit. Avalanche moved from right to left in the view. Note geologist for scale at left side of view.

Transformation from rock slides to rock avalanches occurred during the descent down source mountainsides and required nearly immediate and complete disintegration of source rock, as suggested by the much smaller size of rock fragments comprising the deposits than the spacing of source-rock discontinuities (Jibson et al. 2006), consistent rounding and size distribution of rock fragments from proximal to distal ends of deposits, and most extensive dust-cloud deposits adjacent to source mountainsides and less extensive and consistently distributed dust-cloud deposits along the avalanche deposits. The transformation involved significant thinning; no potential slide or avalanche deposits or evidence of scour were observed on valley walls above the channelized avalanche deposits. Although descent down source mountainsides and transformation to avalanches likely involved violent interactions between rock fragments, significant turbulence was probably not present because rock fragments of different composition were not mixed, as reflected by the compositional zones in the deposits.

Avalanche flow beyond source mountainsides was apparently relatively gentle and laminar; rock-fragment size distributions were consistent with distance from source areas, presumably fragile boulders (those that broke down in place within a year of emplacement) were carried along unharmed, rock fragments of different composition were not mixed, and overrun hillsides were generally not stripped of vegetation or soil. However, laminar flow generally did not occur in the upper part of the avalanches as suggested by the apparent wrinkles, faults, and boulders coated with finer rock fragments and precariously balanced rocks; the rocks would have rolled during laminar flow and toppled or lost their coatings. Therefore, it appears that the upper parts of the avalanches behaved as semi-rigid plugs. Flow of the avalanches probably ceased when they thinned to the thickness of the plugs, resulting in simultaneous cessation of movement as has been reported by eyewitnesses to other avalanches (Heim 1932). At the open-slope avalanches, the plugs appear to have acted as a deformable skin that stretched as the underlying shearing parts of the avalanches thinned and as trailing avalanche material continued to flow down the steeper source mountainside and push the leading material. The inability of the trailing ends of the avalanches to push the leading parts of the avalanches caused wrinkles to form as the leading parts of the avalanches slowed. The trailing ends were preserved as the core compositional zones. At the channelized avalanches, multiple waves formed during flow resulting in formation of overlapping medial and lateral deposits along most of the deposit lengths and overlapping wave deposits at deposit distal ends where the plugs ceased moving. Areas within the distal parts of the avalanches locally slid following cessation of flow, as indicated by observed displacement across faults and substrate damage along some deposit margins.

The characteristics of the avalanches agree with a rheological model such as a viscoplastic, possibly shear-thinning fluid (e.g., Rouse 1961), similar to that proposed for debris flow (Johnson 1970) and avalanches (McSaveney 1978). The characteristics also agree with physically based models that follow Bagnold's (1956) approach (Savage 1979; McTigue 1982; Johnson 1996; Iverson 1997; Iverson and Denlinger 2001). His approach is based on the interaction of sheared collections of particles, such as rock fragments. Shearing causes particle collisions resulting in formation of dispersive forces that reduce interparticle friction, thereby allowing flow and aiding mobility at sufficiently high shear stress. Both the viscoplastic and Bagnold-type of model predict plug flow atop laminar shearing lower parts and can aid prediction of avalanche characteristics. The primary problems with application of these models to predict avalanche flow paths, thicknesses, and velocities are difficulties with defining appropriate rheological models and input parameters for the Bagnold-type models. In addition, avalanche source locations and volumes must also be predicted.

4 CONCLUSIONS

Deposits of seven large avalanches triggered by the November 3, 2002 Denali Fault, Alaska, USA earthquake were examined to gain insight into avalanche movement characteristics. Some of these avalanches were channelized within glacial valleys while others occurred on open slopes. Deposits consisted of abraded rock fragments from clay to boulder sized. The lower parts of deposits were poorly sorted and the upper parts were coarse; this size distribution was consistent from near source areas to deposit distal ends. Boulders coated with finer rock fragments, fragile but unbroken rocks, and balanced rock fragments were common throughout the deposits. Open-slope avalanche deposits generally had consistent thickness of 2-4 m over lengths as great as 4.6 km. Channelized avalanche deposits appeared to consist of overlapped deposits of individual waves. Deposits of individual waves included medial, lateral, and wave deposits, each of which generally had consistent thickness. Zones of different rock type abutted one another in the open-slope deposits and overlapped in the channelized deposits. Apparent wrinkles were observed in the open-slope deposits on the uphill side of confining obstacles. Substrate overrun by avalanches was generally undisturbed and was locally plowed at distal ends of deposits. Deposit characteristics suggest that channelized avalanches flowed as series of waves while open-slope avalanches flowed as coherent units. The avalanches behaved as viscoplastic fluids or dispersive grain flows with semi-rigid upper parts moving upon laminar flowing lower parts. Localized sliding occurred upon cessation of flow.

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