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Volume and shape of the active and inactive parts of the Slumgullion landslide, Hinsdale County, Colorado

by

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VOLUME AND SHAPE OF THE ACTIVE AND INACTIVE PARTS OF THE SLUMGULLION LANDSLIDE, HINSDALE COUNTY, COLORADO

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Mario Parise and Raffaela Guzzi

ABSTRACT

The Slumgullion landslide is located in the San Juan Mountains of southwestern Colorado. It consists of two main landslides. The large landslide occurred about 700 years ago and dammed the Lake Fork of the Gunnison River, forming Lake San Cristobal; it is currently inactive. The smaller part, younger and still active, is entirely within the upper part of the old one.

The pre-landslide topography of the valley within which the landslide originated was reconstructed by using morphometric characteristics of similar nearby valleys that are not filled with landslide deposits. The longitudinal gradient of the old Slumgullion Creek was computed by comparison with other streams and the value so obtained was checked by statistical analysis. The shape of the valley walls outside the boundaries of the landslide, the gradient of the tributary thalwegs, and the forms of the other valleys all provided further constraints for the reconstruction of the pre-landslide topography.

The comparison of pre-landslide and post-landslide topography on several cross sections along the landslide allowed the computation of the debris volume, equal to 168 x 10^6 m^3, and of the detached mass volume, equal to 109 x 10^6 m^3.

The active landslide is in our opinion a remobilization of part of the old landslide. Its volume was estimated from a combination of geometric and displacement data, postulating a constant flux of material through cross sections within the landslide; the estimate is 19.5 x 10^6 m^3, that is, only about twelve percent of the overall volume.

If the landslide material is assumed to be perfectly plastic, the yield strength can be computed by using the methods relating the strength of the material of an earthflow to the shape of its terminal part, as proposed by Nye (1951) for glaciers and by Johnson (1970) for debris flows. The values obtained for the Slumgullion landslide are in the range from 2.64 to 5.09 x 10^6 dyne/cm^2.

INTRODUCTION

The Slumgullion landslide is located in the San Juan Mountains of southwestern Colorado, about three km southeast of the town of Lake City (figs. 1 and 2). It consists of two distinct parts. The large part, nearly seven km long, extends from a 250-m-high scarp on the edge of the Cannibal Plateau to Lake San Cristobal on the

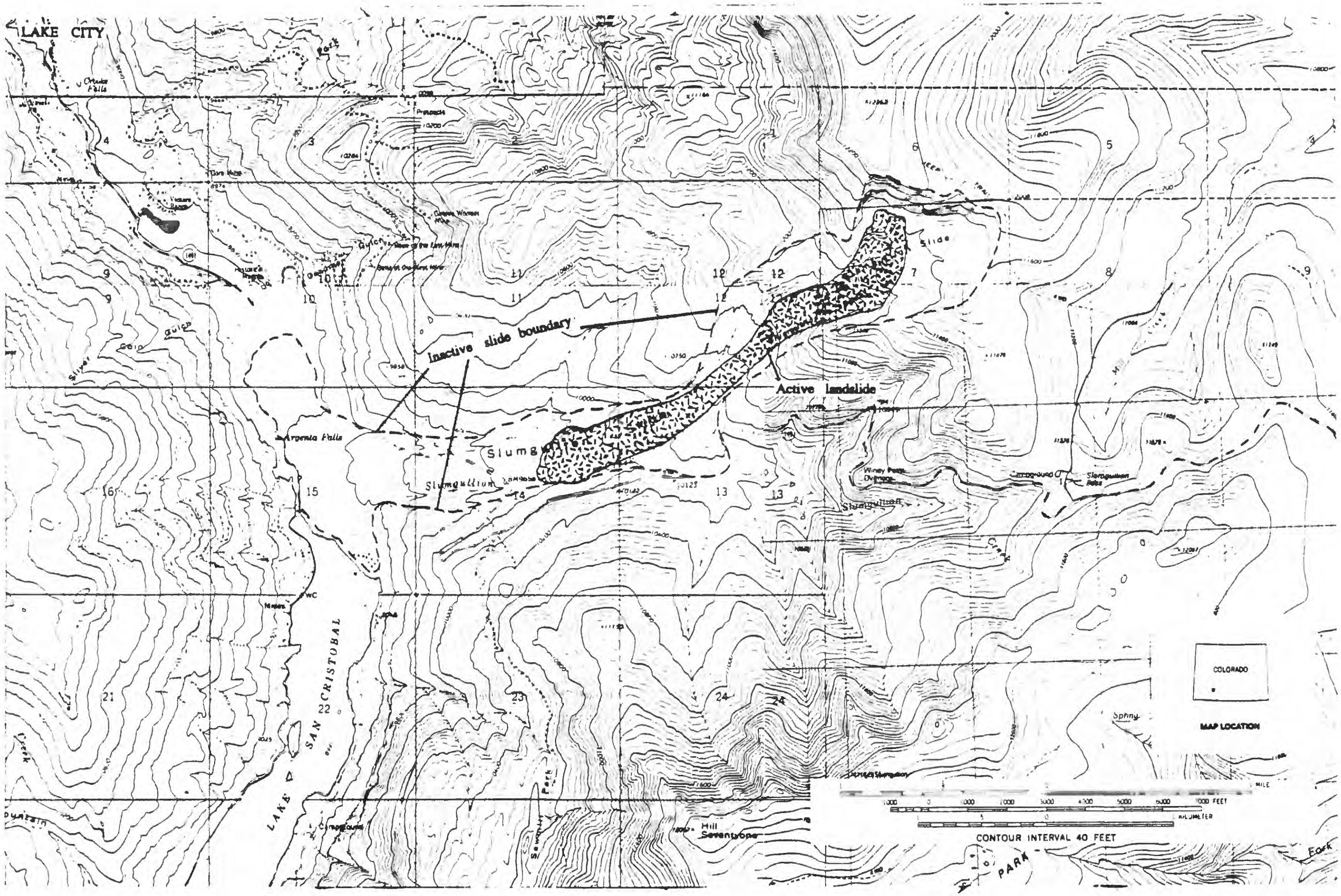

Fig. 1 - Topographic map and location of the studied area. The boundary of the old landslide is dashed. The active landslide, entirely within the boundaries of the ancient one, is highlighted.

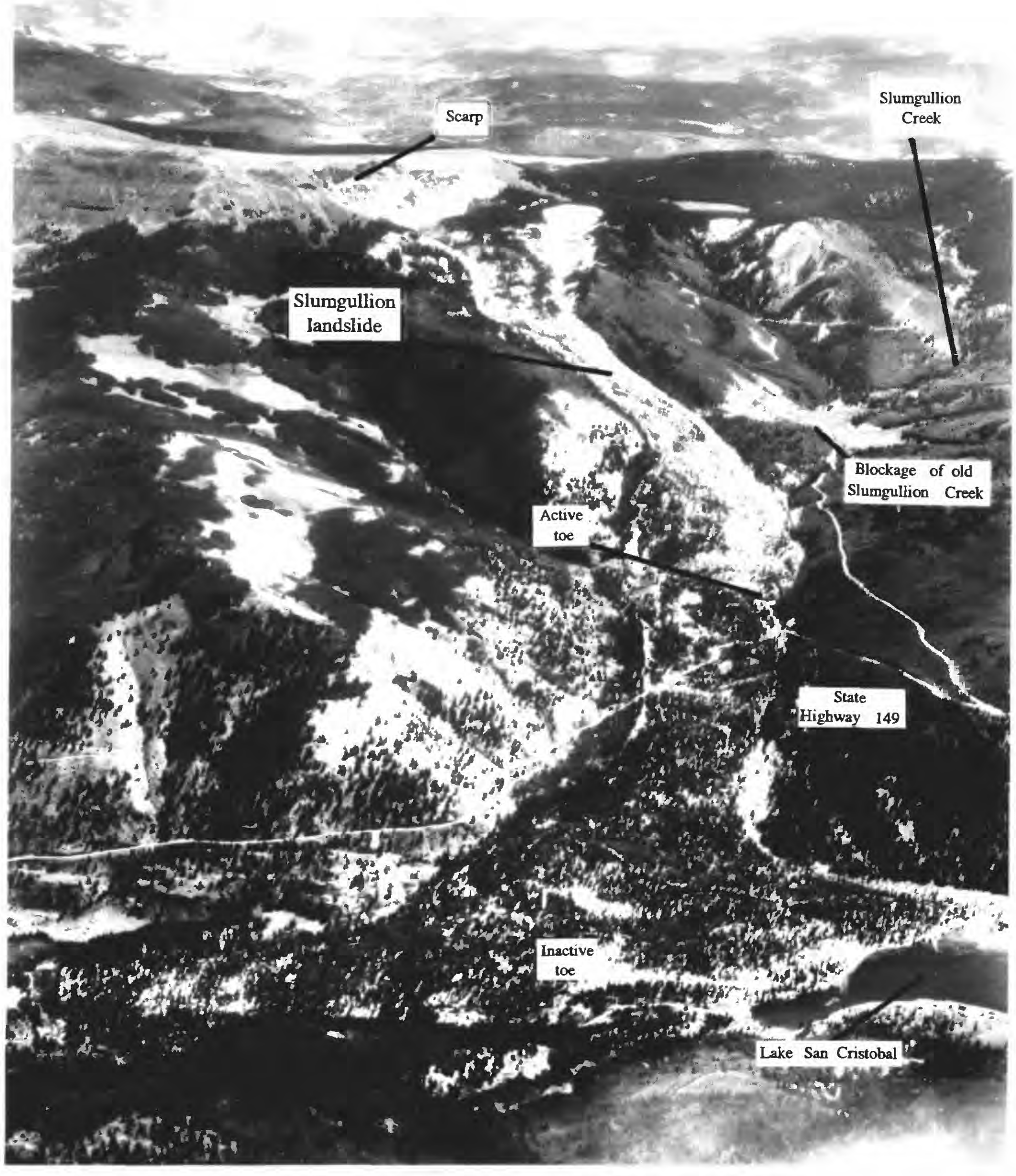

Fig. 2 - Eastward view of the Slumgullion landslide. Lake San Cristobal, created by damming the Lake Fork, is at the lower right side of the view. The inactive landslide extends from the lake uphill to the prominent scarp in the upper middle of the view. The toe of the active landslide is the light-colored, bulbous area just uphill from where State Highway 149 crosses the landslide. The active landslide occurs within the boundaries of the inactive landslide and apparently represents reactivation of a portion of the old landslide. Photograph (# 1485 cr) taken in 1958 by John S. Shelton (used by permission).

Lake Fork of the Gunnison River. This landslide created Lake San Cristobal by damming the Lake Fork about 700 years ago (Crandell and Varnes, 1960, 1961); it is currently inactive. The smaller part, about four km long, occurs entirely within the upper part of the 700-year-old deposit; it is an active landslide that has been moving for about 350 years, with a maximum measured velocity of 6.0 meters per year (Crandell and Varnes, 1960, 1961). It can therefore be classified as slow movement, according to the rate of movement scale of Varnes (1978). The purpose of this paper is to describe the methods and the results of measurements of the volumes of the active and inactive parts of the Slumgullion landslide.

The Slumgullion landslide is one of the most active and well known landslides in the United States, but has received relatively little detailed quantitative study. It was first described by Endlich (1876) in the report of the Hayden Survey of 1874. Later, the landslide was described by Howe (1909) and photographed by Whitman Cross (plate XXB in Howe, 1909). Also, the landslide was mentioned in Atwood and Mather (1932) and Burbank (1947). Crandell and Varnes (1960, 1961) studied the landslide complex during 1958-60 and described the ages of sliding as well as the rates of movement at various points on the surface of the landslide. Since 1960, there reportedly have been few published studies of the landslide. The U.S. Bureau of Land Management and U.S. Forest Service mention the landslide in educational markers along State Highway 149, which crosses the lower part of the inactive landslide and courses along the south side enroute to Slumgullion Pass (figs. 1 and 2).

In 1990, the U.S. Geological Survey (U.S.G.S.) began a systematic study of the Slumgullion landslide. Horizontal and vertical positions of reflective panels were established around the perimeter of the landslide by a field party led by D.J. Varnes. Two sets of aerial photographs were taken, one each at scales of 1:6,000 and 1:14,000. Previously, in 1985, reflective targets had been set by R.L. Schuster, U.S.G.S., and aerial photographs were taken at a scale of 1:12,000 by the Colorado Geological Survey. A digitally stored topographic map (2 m contour interval) was prepared from the 1990 photographs by James Messerich. The map was reproduced at a scale of 1:1,000 for recording field observations.

This paper is the first of a two-part description of the landslide. Authors, Mario Parise and Raffaela Guzzi, are graduate students at the "Istituto di Ricerca per la Protezione Idrogeologica nell'Italia meridionale ed insulare" (IRPI), Cosenza, Italy, and have conducted this investigation as part of a cooperative exchange with the U.S.G.S. Fieldwork was conducted during two field seasons in 1990 and 1991. This first part discusses the determination of the size and shape of the active and inactive parts of the landslide. The next part, by Guzzi and Parise, describes the results of mapping the features exposed at the surface of the active landslide and presents data on the rate of movement at different points on the landslide surface.

In this paper, the reconstruction of the pre-landslide topography is used to compute the volume of the large, inactive landslide and the volume of material missing in the source area.

The volume of the currently active landslide was computed from a combination of geometric and displacement data. The final part of this paper deals with an estimation of the strength of the material involved in the landslide using the equations relating the strength to the shape of the terminal snout developed by Nye (1951, 1952b) for glaciers and Johnson (1970) for debris flows.

Acknowledgments

The Colorado Geological Survey obtained the 1985 aerial photographs. The U.S. Bureau of Land Management and U.S. Forest Service permitted access to study the landslide. U.S.G.S. support was provided by David and Katharine Varnes, Robert Schuster, Rex Baum, Richard Madole, William Smith, William and Jill Savage, William Brown III, and Robert Fleming. David Varnes and Robert Fleming reviewed the manuscript. Philip Powers, U.S.G.S., helped work on the Surfer computer graphics program. Sandra Natoli, University of Rome, drafted some of the figures. Giovanni Crosta, University of Milan, participated in the field mapping. Prof. Marino Sorriso-Valvo served as advisor to the study from the IRPI of Cosenza.

To these people and organizations, we express our sincere appreciation.

VOLUME OF THE ANCIENT LANDSLIDE

The volume of the ancient landslide can be estimated from the shape of the buried valley that underlies the landslide deposits.

There are a surprising number of constraints on the shape and size of the buried valley. First, the smooth side slopes extend for hundreds of meters above the buried valley floor providing extensive data for projecting slopes under the landslide debris. At the toe of the landslide, part of which is under Lake San Cristobal, Crandell and Varnes (1961) have provided a measure of the maximum depth of the lake from soundings in the lake. Gradients of tributaries to the buried valley can be projected to estimate the maximum depth of the thalweg. And finally, the shapes of other valleys in the area that are not filled with landslide deposits can be compared to the shape of the buried valley of Slumgullion. None of these estimators, the shape of the valley walls, the gradient of the tributary thalwegs, and the forms of similar nearby valleys are totally independent, and each provides a sort of check against the other. The computed volume can be further checked against the volume of the mass that is projected to be missing in the area of the headscarp.

The ancient landslide was emplaced through collapse of the headwall and flow of the debris down a tributary to Lake Fork. Along the flanks of the landslide deposit and parallel to the movement direction, there are smooth levees or flank ridges that were created by the movement. In many places, there is only one or more commonly two such flank ridges. One ridge is typically the product of current movement. In a few places, the active boundary may coincide with the ancient boundary. More commonly, outside the active flank ridge, one or more additional flank ridges resulted from prehistoric movement. These older ridges are covered with mature conifers and aspen trees, and their positions and ages have not yet been studied. The history of movement of the ancient complex has not yet been developed from our work up to now. For our present purposes, we consider the ancient landslide to have occurred as a single episode of movement.

At the head of the landslide, there is a large bowl-shaped reentrant that is the source of the landslide debris (fig. 1). The scarp is very steep, in places nearly vertical, and about 250 m high. Rocks exposed in the scarp include hydrothermally altered volcanic flows and breccias as well as unaltered tuffs, and flows. The hydrothermal weathering transformed much of the material into a soft clay (mostly montmorillonite) and sand formed by residual rocks. Gypsum is an abundant product of chemical alteration (Howe, 1909; Crandell and Varnes, 1960; Crandell and Varnes, 1961). The same materials exposed at the headwall can be identified on the surface of the landslide, in variable quantities and shapes. Overall, the surface appearance is a mixture of yellow, grey, brown, red, and purple material that is mostly fine grained with patches of large angular fragments of columnar jointed flow rock. Isolated boulders of dense volcanic rock are scattered over the landslide surface; in some places they are collected in linear downslope-trending groups that appear to have been concentrated by the movement process. The name of the landslide, Slumgullion (Howe, 1909), which refers to a type of miner's stew containing many ingredients, is appropriate.

Downslope from the high scarp, landslide deposits filled a pre-existing valley that was tributary to Slumgullion Creek (fig. 1) and then went on to block the Lake Fork of the Gunnison River and create Lake San Cristobal. Lobes of landslide material extend both upstream and downstream in the Lake Fork valley from the point of intersection with the buried valley of the old Slumgullion Creek.

The ancient Slumgullion landslide also blocked part of the drainage basin that carried the main part of Slumgullion Creek. The blockage, which occurs in Section 13 and shown on fig. 1, was created by movement from the left flank of the ancient landslide up Slumgullion Creek a distance of about 600 m to the southeast. The lake that was formed there has drained, but the flat-bottomed floor of part of the old lake abuts the lobe of Slumgullion landslide material.

Elsewhere along the trend of the landslide in the blocked tributary to Lake Fork, the smooth slopes of the old valley walls are abruptly broken by landslide deposits. Nowhere is there evidence that these valley slopes were involved in the movement of the landslide. The landslide has filled the ancient valley with debris, and the contact between the debris and the old valley wall is abrupt and conspicuous.

Method of volume estimation

The first step in the reconstruction of the valley underlying the prehistoric landslide was to study the morphometric characteristics of the present valley, and to compare them with the characteristics of several other drainage basins and their streams in the area around Slumgullion landslide. The basins were chosen to be comparable with the Slumgullion site in size of drainage area and underlying rock types.

Especially in volcanic areas, changes in geology greatly influence the shape of the valleys and the hydrologic and morphologic characteristics of the streams.

At the Slumgullion landslide area, as throughout the southwestern San Juan Mountains, the topography generally is controlled by the erosional resistance of different types of volcanic rocks. Usually the steep cliffs correspond to flows, while unconsolidated tuffs and breccias produce gentler topography.

Many areas, however, in spite of outcrops of volcanic flows, are characterized by only moderate relief, because of the presence of superficial material and of the decomposed condition of underlying rocks. For instance, the forms of most of the examined basins, including the Slumgullion basin, are modified by the presence of colluvium. These deposits are derived from the physical disintegration and chemical alteration of volcanic rocks and their constituents range in size from silt to boulder. Locally, hillslopes also contain landslide and glacial moraine deposits (Lipman, 1976).

The streams in the valleys comparable to Slumgullion basin in size have gradients that are very close to the gradients in the Slumgullion basin. Basins of smaller size have stream gradients that are four to five degrees steeper than Slumgullion.

The comparable valleys also usually have rather steep sides and are V-shaped, with a narrow thalweg and no flood plain. The streams are generally located in the middle of the valley bottom or slightly closer to the slope with the steeper valley wall.

On the basis of these considerations, we believe that the old Slumgullion Creek was located closer to the right side of the valley, characterized by steeper hillslopes. In our reconstructed profile, the creek was drawn with a rectilinear course, connecting it in its upper part to its present course outside the limits of the influence of the landslide.

The morphometric characteristics and the present shape of the valley where the Slumgullion landslide flowed were studied by drawing a series of transverse cross sections. The valley has an orientation northeast-southwest in the upper part and about east-west in the middle lower part of the landslide. The transverse profiles across it show north-facing slopes that are slightly less steep than the south-facing slopes. The difference is in the range of three to five degrees (average slope gradients are, respectively, 15-17 degrees and 18-20 degrees). Locally, on the left side of the valley, the slope has a convex profile. The convex shape is created by glacial moraine (Lipman, 1976). This type of material usually has a hummocky topography, and it commonly has local changes in gradient. Exposures of glacial till are visible on the cuts along State Highway 149, just south of the Slumgullion landslide. On the upper part of the valley, the average slope gradients maintain more or less the same values, increasing locally to 23-24 degrees.

The Lake Fork of the Gunnison River is the largest river of the area. The Lake Fork valley is U-shaped, with rectilinear slopes and a quite large and flat bottom. The average valley wall gradients are about 27°- 28°, with maximum value of 41°. There is no significant difference in the gradients between the two valley sides.

Before the ancient Slumgullion landslide occurred, the Lake Fork should have been closer to the right side of the valley, following a large bend to the left caused by the presence of Red Mountain at the west.

The knowledge of the point of maximum depth of Lake San Cristobal, combined with the computation of the longitudinal gradient upstream and downstream from the landslide material, allowed us to reconstruct the pre-landslide contour lines along the bottom of the river valley. At elevation about 2,700 m (8,800 feet) downstream the reconstructed old Lake Fork was connected to the present course of the river. The maximum depth of Lake San Cristobal (27.5 m) obtained from soundings in the lake by Crandell and Varnes (1961) was not adjusted for sediment that has accumulated in the lake since damming.

Once we had reconstructed the shape of the old valley of Lake Fork, we could estimate the elevation of the junction with Slumgullion Creek to be about 2,700 m (8,800 feet). The knowledge of this point and of its elevation were the starting points for the reconstruction of the longitudinal profile of the buried valley.

The present Slumgullion Creek has a length of about 6,300 m, with a difference in elevation between its head and mouth of about 800 m; its longitudinal slope gradient is 7.26°.

The course of Slumgullion Creek has not been affected by the landslide from approximate elevation 3,130 m (10,300 feet) uphill. In the lower part, at the present, it runs along the left side of the landslide, on the inside of the main old flank ridge. It also receives most of the water from the more or less ephemeral streams flowing on the slide.

The longitudinal profile of the old Slumgullion Creek was reconstructed by comparison with profiles of other streams. The streams most comparable to Slumgullion Creek, in regard to length and catchment basin area, are Larson Creek and Independence Gulch. They contain a basin area of 20.51 km^2 and 16.48 km^2, and overall longitudinal gradients of 7.35° and 7.07°, respectively (table 1; figs. 3a and 3b).

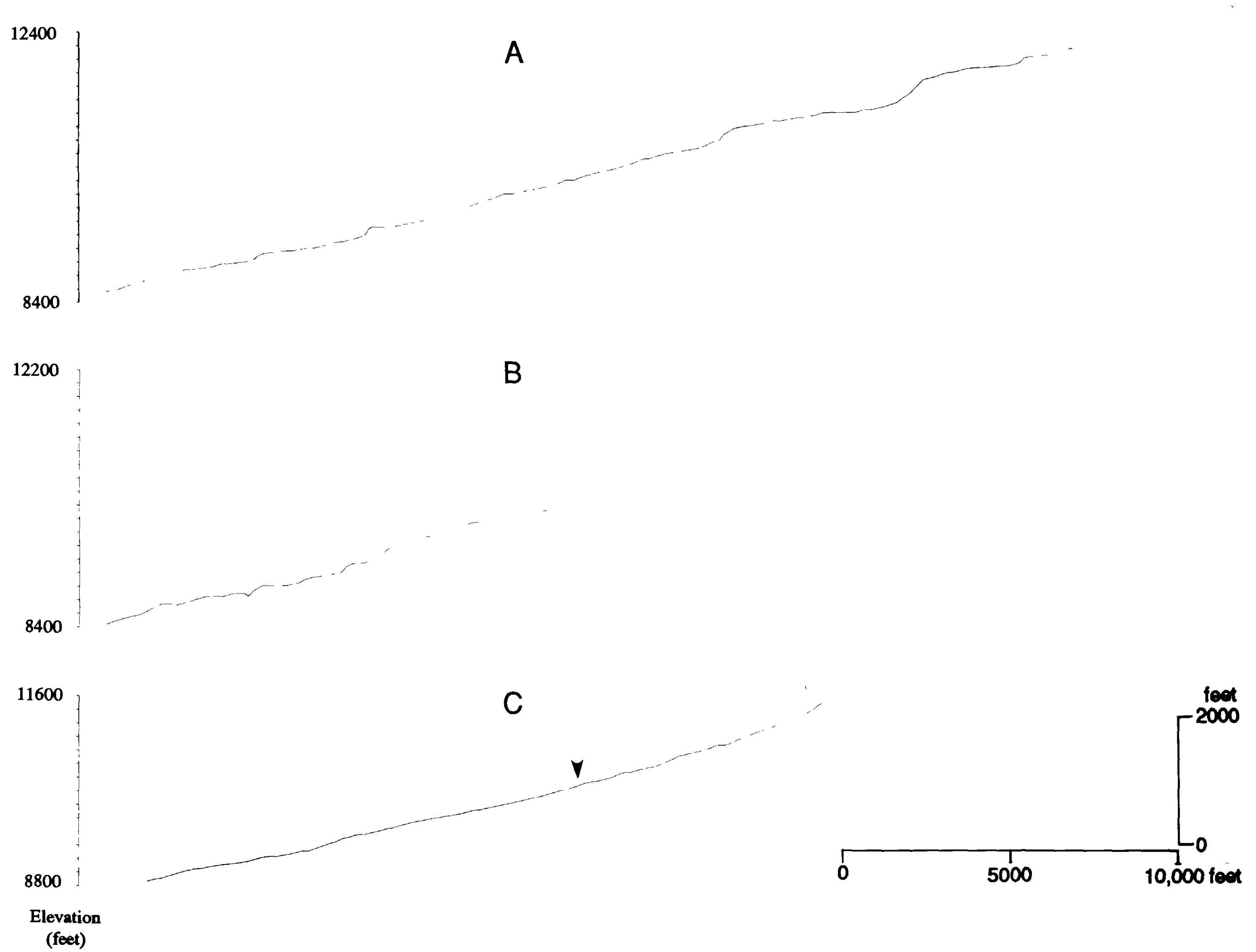

Fig. 3 – Longitudinal profiles: a) Larson Creek; b) Independence Gulch; c) old Slumgullion Creek. Uphill of the arrow shown in figure, the longitudinal profile of the Slumgullion Creek is unchanged, because in that area the creek was not affected by the landslide; downhill of the arrow, the landslide blocked and shifted the old Slumgullion Creek. That part of the longitudinal profile of the old creek was reconstructed by comparison with Larson Creek and Independence Gulch; they are the streams most comparable to Slumgullion Creek in regard to length and catchment basin area.

TABLE 1 - Morphometric characteristics of catchment basins and streams. A = catchment basin area; L = stream length; Δ = difference in altitude between spring and mouth.

	A (km^2)	log A	L (m)	Δ (m)	longitudinal gradient (°)
Alpine Gulch	33.44	1.52	8,640	1,158	7.63
Cascade Gulch	4.32	0.63	3,864	927	13.46
Crystal Creek	4.44	0.65	3,648	865	13.35
Independence Gulch	16.48	1.22	9,096	1,127	7.07
Larson Creek	20.51	1.31	8,784	1,134	7.35
Nourse Creek	4.67	0.67	3,960	853	12.16
Red Mountain Gulch	8.46	0.93	4,584	853	10.55
Sparling Gulch	13.99	1.15	5,028	817	9.23
Wade Gulch	6.21	0.79	4,608	829	10.20
Old Slumgullion Creek	20.15	1.30	6,096	817	7.63*

* computed gradient

The longitudinal profiles of Larson Creek and Independence Gulch were smoothed a little, in order to eliminate the changes due to local variations. Along each of them, the gradient every 150 m was computed. Knowing the relationships between the lengths of the streams, we computed the gradients along the old Slumgullion Creek. This method has been applied to data from both Larson Creek and Independence Gulch, giving two computed estimates of the longitudinal profile of the old Slumgullion Creek. By making an average of the gradient values of the two profiles every 60 m, we obtained the longitudinal profile of old Slumgullion Creek (fig. 3c). It has a gradient of 7.63°.

As a further check on the computed longitudinal gradient of old Slumgullion Creek, we made a statistical analysis of stream basin parameters for nine nearby valleys. The analysis aimed to establish relationships between the longitudinal stream gradients and other morphometric parameters (table 1).

For each stream the catchment basin area (A), its logarithm (log A), the stream length (L) and the difference in altitude between spring and mouth (Δ), have been plotted versus the longitudinal gradient of the stream. A regression line and the correlation coefficient have been computed for each diagram.

The best relationships were found to be "A versus longitudinal gradient" and "log A versus longitudinal gradient". The latter, in particular, is linear and shows the best correlation coefficient, with $r = -0.91$.

The diagram "log A versus longitudinal gradient" is shown in fig. 4; the equation of the regression line is

$$\text{longitudinal gradient} = -7.12 \log A + 17.16$$

Applying on this diagram the logarithm (1.3) of the Slumgullion Creek catchment basin area (20.15 km^2) we calculated a longitudinal gradient of 7.9° for the old course of the creek.

This value is considered close to the one we estimated previously from the direct comparison with the other streams. This latter value, 7.63 degrees, has been accepted for the reconstruction of the topography of the buried valley.

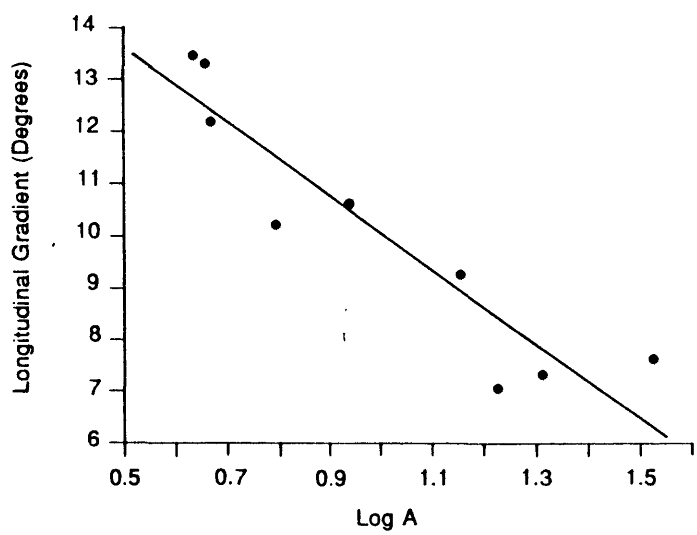

Fig. 4 - Regression line for the relationship between streams longitudinal gradient and logarithm of their catchment basin area.

Pre-landslide topography

Along the length of the Slumgullion landslide, 68 transverse cross sections were drawn at regular intervals of 0.5 cm on the map at a scale of 1:24,000. Eleven typical cross sections are shown on fig. 5, with a map showing their location.

The buried valley can be obtained by simply extending and connecting the profiles of the side slopes. The V-shaped valley that is obtained is typical of most of the basins in the area around Slumgullion.

A topographic map was prepared of the buried valley using the 68 profiles that were spaced every 120 m along the landslide. Control for the map was provided at the intersections of landslide topography with non-landslide topography and the course of the Slumgullion Creek. The location of the creek along each profile, and the distance (d) between the junction of Lake Fork and the buried Slumgullion Creek and each transversal profile have been used for control.

The elevation of the creek along each profile, and consequently the maximum deposit thickness, was drawn out from the longitudinal profile of the Slumgullion Creek previously obtained.

Connecting the courses of the contour lines outside the boundaries of the landslide with these points, the pre-landslide topography along the Slumgullion Creek was drawn.

From elevation ≈ 2,990 m (9,800 feet) uphill, the same procedure previously described was completed for the reconstruction of the upper valley, where a tributary of the old Slumgullion Creek probably flowed.

Figure 6 shows the map obtained. In the figure, both the courses of old Slumgullion Creek and Lake Fork are drawn, as well as the overall boundaries of the ancient landslide.

The main topographic changes caused by the landslide are: 1) filling of the valley, 2) creation of Lake San Cristobal, 3) creation of large scarp and reentrant, and 4) shifting of Slumgullion Creek. The pre-landslide morphology consisted of a 25° slope (average value), that locally increased to 30° on the western border of the plateau. From its upper part, the buried valley starts with a course oriented NE-SW, and then almost E-W, until it reaches the junction with the old Slumgullion Creek, at an elevation of ≈ 3,072 m (10,080 feet). The lower part of the valley, where the old Slumgullion Creek flowed, was both steep and V-shaped; in its reconstruction we maintained the present average slope gradients.

There are changes in width of the valley along the length of the slide. It narrows markedly in the area between elevations of 3,145 m and 3,206 m (10,320 feet and 10,520 feet contour lines in fig. 1).

To facilitate our computations, the maps and profiles were digitized. In figure 7, we show the results of an experiment to draw perspective views of the Slumgullion landslide area.

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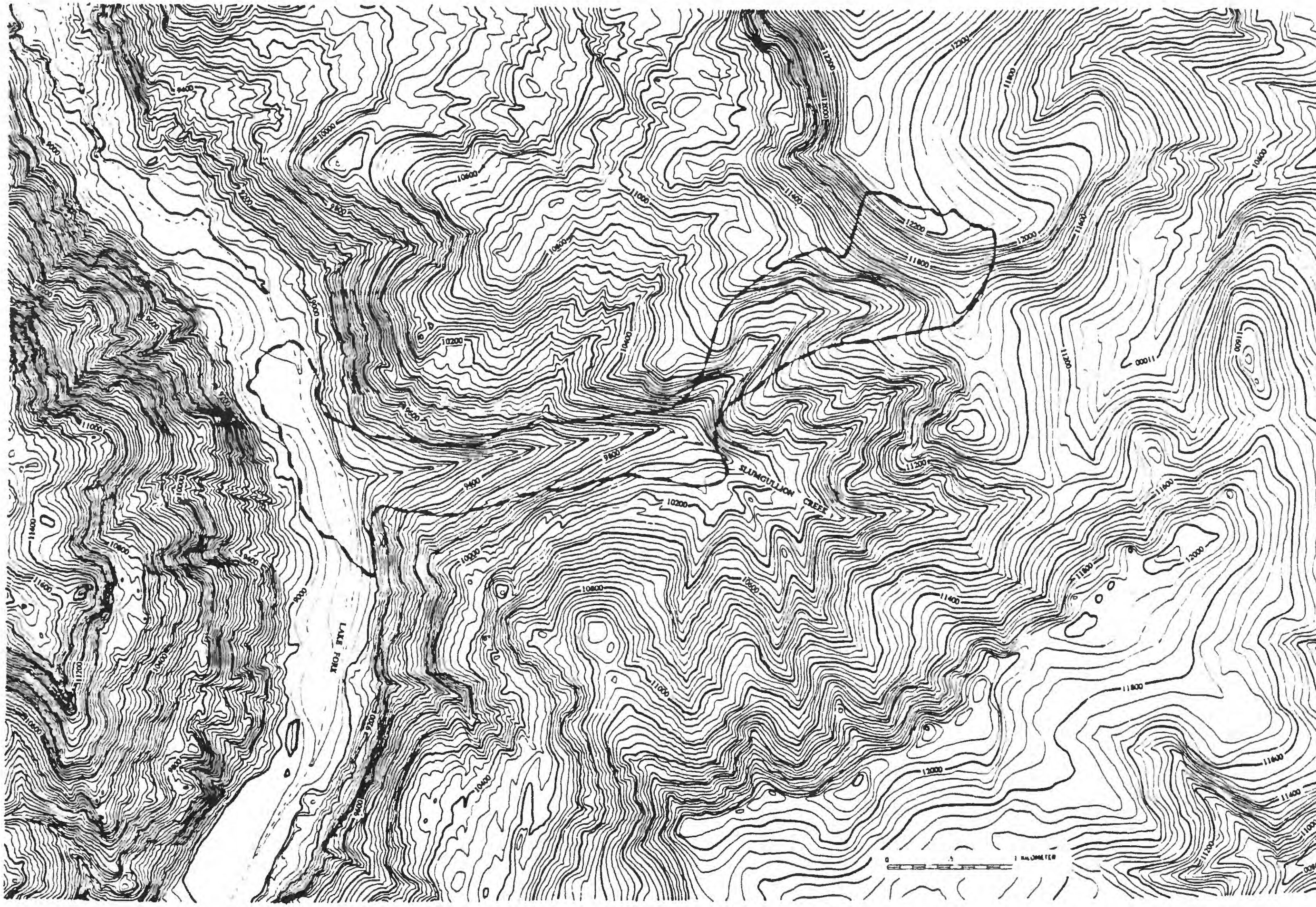

Fig. 6 - Pre-landslide topographic map, showing the boundary of the ancient landslide in heavy dashed line. The old courses of Lake Fork and Slumgullion Creek are drawn as dashed lines. Elevation in feet.
For explanation of the method of reconstruction of the pre-landslide topography see text.

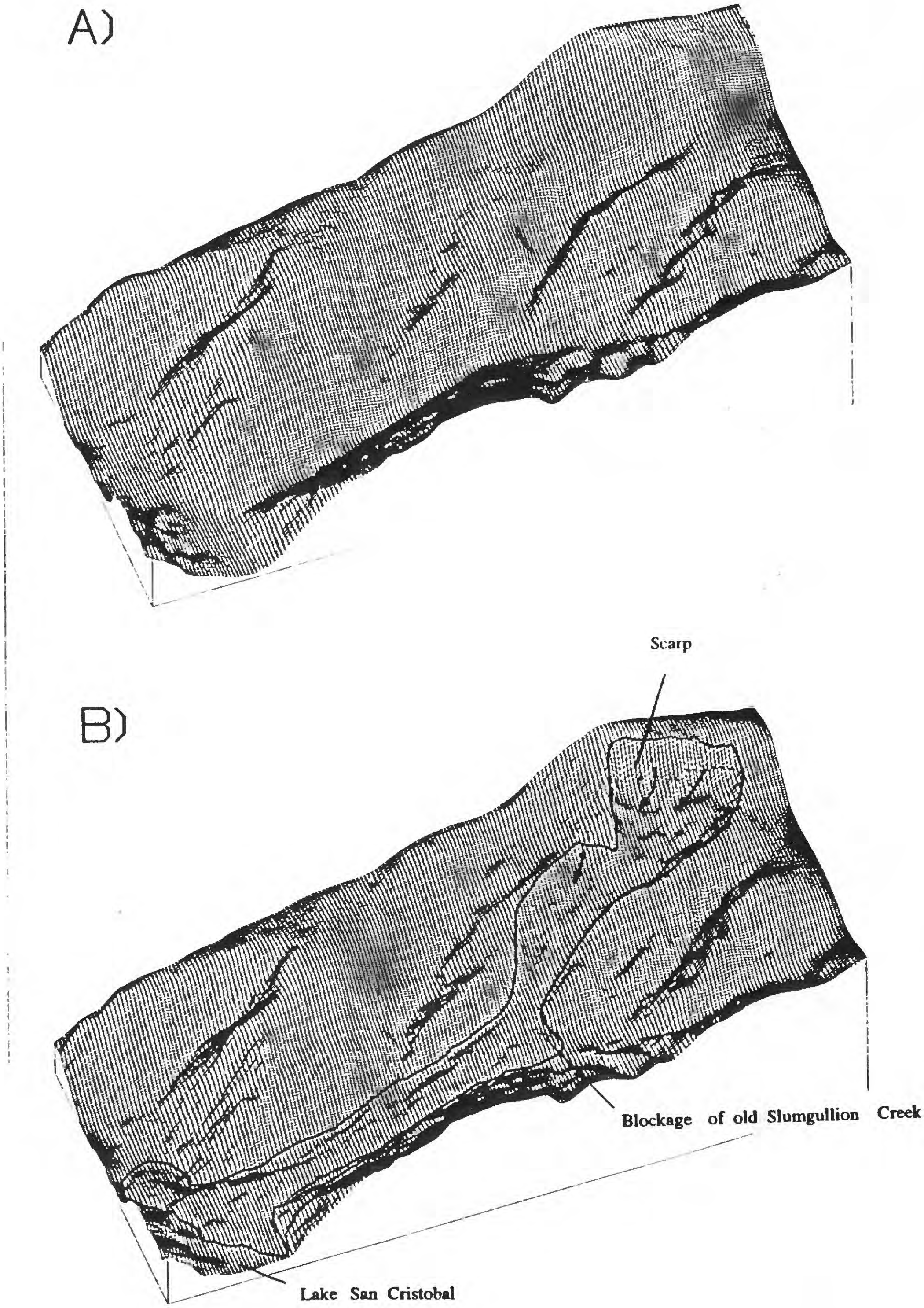

Fig. 7 - Slumgullion landslide elevation models: a) pre-landslide situation; b) present situation. On the present situation model, the boundary of the ancient landslide is shown.

Overall volume computation

The volume of the landslide deposit was computed by comparison of the pre-landslide and the present topography on the transverse cross sections along the landslide. We estimated the cross sectional shape and depth of burial of the valley at several locations along the length of the landslide; cross sectional areas were then integrated over the length of the landslide to produce a volume estimate.

The validity of the pre-landslide topography required a coincidence between the landslide boundaries shown in fig. 1 and the deposit boundaries on the cross sections.

The results we had were in good agreement, with few exceptions apparently caused by fluvial erosion or minor landslides that removed from or added material to the landslide. The cross sectional areas of the deposit, measured with a polar planimeter, range from 1,600 m^2 (cross sections in the upper part of the slide and about at the tip of the toe) to 55,900 m^2 (cross section at toe of inactive landslide where it joins the valley of Lake Fork). The maximum debris thickness of 140 m occurs on cross section 6-6' (fig. 5).

The total landslide volume, obtained by integrating the cross section areas over the length of the slide, equals 168 x 10^6 m^3.

Alternative method of volume estimation

The volume of the landslide deposit can be checked in a crude way against the volume that appears to be missing from the headscarp area (fig. 8). There is less control on the reconstruction of the pre-landslide topography in the head of the landslide than underlying the landslide because we must assume the shape, at the ground surface, of a mass that is no longer present. Our assumption is that the pre-landslide topography was simply the continuation of the topography from each side of the edges of the scarp. Nineteen profiles were drawn normal to the scarp from the crown and extending onto the upper part of the landslide deposit.

There is a smaller source of landslide debris along the upper right flank of the landslide between 3,230 m and 3,718 m (10,600 and 12,200 feet). Of the 19 profiles drawn, 11 were drawn across the main headscarp and 8 across the smaller source area. Four of the typical profiles are shown in fig. 8 along with a map showing their location.

The missing volume was computed by comparison of cross sections of pre-landslide and present topography; it is 109 x 10^6 m^3 with about 7 x 10^6 m^3 coming from the subordinate scarp area on the upper right flank.

In raw numbers, 109 x 10^6 m^3 is only about 2/3 the estimated total volume of the landslide of 168 x 10^6 m^3. There are several possible sources for this difference. First and most significant is the bulking that occurs when intact rock is transformed into landslide debris. There is very little published information on

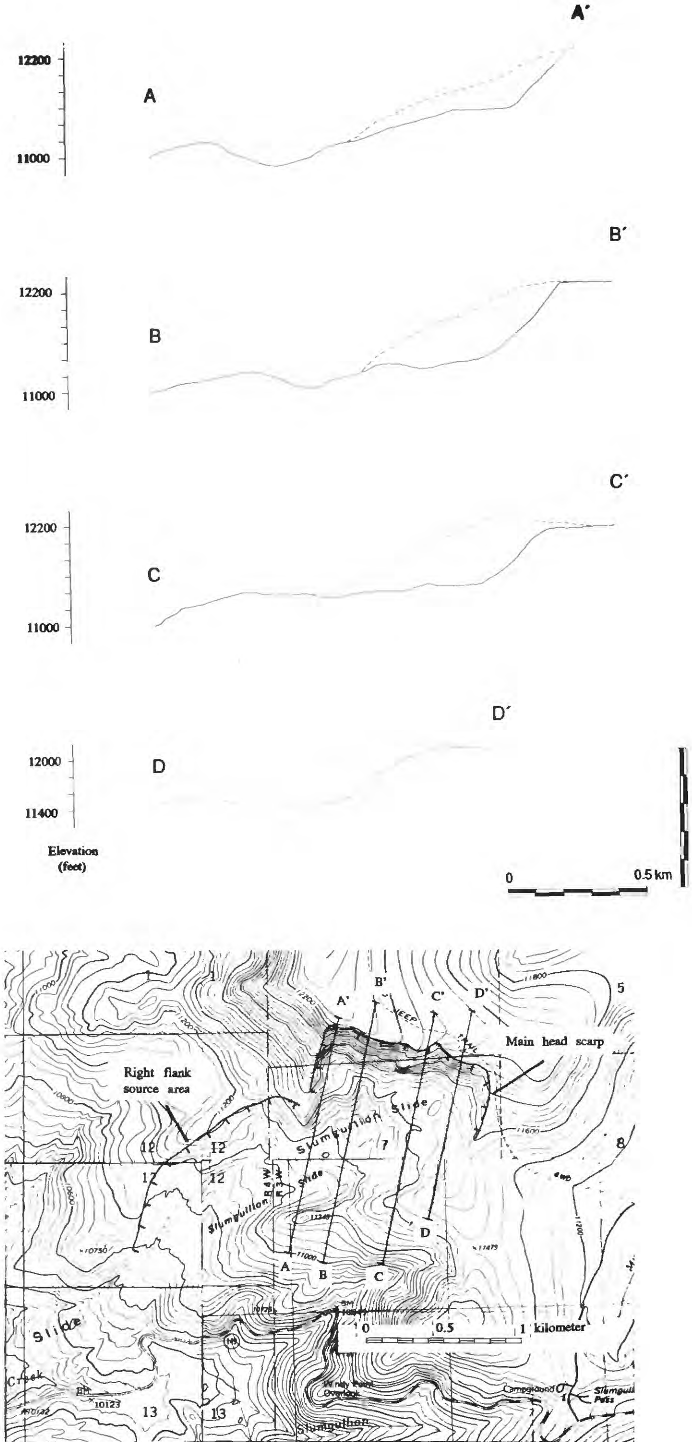

Fig. 8 - Cross sections for the computation of detached mass volume and map showing their location. Present topography in solid line; pre-landslide topography in dashed line. The pre-landslide cross sections were drawn from the reconstruction of the pre-landslide topography (fig. 6). The map for location shows both the main headscarp and the source area on the upper right flank of the landslide.

bulking caused by landsliding when the material become soil-like in character and flows. For other types of landslides like rock slides and rock avalanches, where the material is completely broken and displaced, a bulking in the range of 25 - 35 % has been observed (Hadley, 1978; Mc Saveney, 1978; Plafker and Ericksen, 1978; Cruden, 1980; Nicoletti and Sorriso-Valvo, 1991). Assuming a bulking factor of 30 %, the comparative volumes are 142 x 10^6 and 168 x 10^6 m^3.

The difference between the raw values of volume would require a bulking factor of 54 % to bring them into agreement. This amount of bulking seems unreasonably large.

Another definite source of underestimation of pre-landslide volume is the upper part of the depleted mass (WP/WLI, 1990) that currently occupies part of the source material scar. We did not include any of volume of landslide deposit as also occupying part of the original source volume. Clearly, part of the source of landslide deposit is now covered with debris, but we have no basis to estimate the amount.

The difference we obtained using a bulking factor of 0.3 is probably as close as we can estimate the volumes, given the data. The 1:24,000 topographic map has a contour interval of about 13 m (40 feet); thus the maximum thickness of the landslide debris is only ten times our measurement interval. Given the precision of all the data for pre-landslide and post-landslide, topography and potential errors introduced in projecting topographic gradients and profiles from other nearby valleys, the discrepancy between 142 and 168 million of cubic meters is not serious.

VOLUME OF THE ACTIVE LANDSLIDE

Estimating the volume of the currently active part of the Slumgullion landslide is more difficult than estimating that of the prehistoric slide. For the old landslide, the morphology of the deposit, the form of the headscarp, and the unmodified topography extending outside the boundary of the landslide deposits all provided limits to the pre-landslide topography.

The currently active landslide, however, is entirely inside the boundaries of the old landslide. Crandell and Varnes (1961) suggested that the active landslide headed in the same basin as the older landslide, and actively moving material was being displaced over the surface of the old landslide. They pointed out, however, the difficulty of explaining how the active landslide could have reached as far as its present position in only 350 years, if movement rates have been constant. They mentioned, but did not favor, the possibility that the active part might be reactivation of the older, stable flow. On the otherhand, we believe that the currently active part of the landslide was mobilized from the old landslide deposit. Admittedly, evidence supporting an explanation is circumstantial.

The data we have that are relevant to reconstruction of the volume of the active flow are systematic measurements of displacements by Crandell and Varnes (1961) and a few short-time measurements by Baum and Fleming (unpubl. data, 1990, 1991). We also have a few observations pertinent to the shape of the failure surface from our mapping of the landslide surface and observations and/or measurements of displacement vectors.

By postulating a constant flux of material we can use displacement data to estimate landslide volume. Crandell and Varnes (1961) observed that movement rates at a given point were nearly constant from season to season and over a period of several years. We have observed, nearly 30 years later, that rates are about the same as those measured by Crandell and Varnes. Furthermore, the rates are highly variable from place to place and, crudely, are inversely proportional to the width of the landslide.

The idea of a constant flux is that the same amount of material per unit time is passing through each and every cross section of the landslide at any given time. If the depth of sliding is known along one section across the landslide, the cross sectional area for that part of the landslide can be calculated simply from the width and thickness. Then, the known cross-sectional area multiplied by the velocity there is equal to the product of area and velocity for any section.

For this estimate, we had no borings or other ways to determine depth to the failure surface. Lacking that, we obtained the vector of displacement of the active toe which had been measured by Baum and Fleming (unpubl. data, 1991) as horizontal. Material is emerging horizontally from the ground and moving over the old landslide surface; the local height of the landslide toe is therefore equal to the thickness of the active landslide. Using the derived flux and the velocities reported by Crandell and Varnes (1961) for five points on the landslide surface, and assuming that the velocities measured at the surface are constant with depth, we then computed depths to the failure surface of these points and drew the longitudinal section shown in fig. 9.

The estimated surface of rupture is generally parallel to the ground surface, with an average thickness of 13 m. From the initial horizontal slope at the active toe, about 240 m uphill it reaches the maximum thickness of 48 m. The thickness decreases from there to its minimum value, about 150 m upstream of the largest pond on the landslide (fig. 9).

The most compelling evidence that the active landslide results from remobilization of the old, inactive landslide is based on an observation at a point about 200 m downslope from the point of minimum thickness (fig. 9). There, lacustrine sediments that were deposited horizontally dip back into the slope about 6 degrees (Guzzi and Parise, 1991). This change in dip has occurred over a distance of 85 meters, from the upslope end of the large pond.

Fleming and others (1988) noted in large landslides in Utah that the shape of the failure surface can be inferred from changes to surface features. At the landslide in Manti Canyon, Utah, the positions of ponds of water on the landslide surface remained fixed

(p. 21 follows -
p. 20 oversize plate)

while the sediments deposited in the ponds were transported downslope. The change in dip of the sediments was equal to the change in slope of the failure surface over the interval displaced.

In the case of the active Slumgullion landslide, the dip of the rupture surface back into the hillslope marks where the original failure surface of the active landslide came to the surface of the old landslide. This now is the upper limit of the foot of the active landslide, that is, the part of the landslide that moved beyond the toe of surface of rupture, and that now lies above the original topography of the ancient landslide (WP/WLI, 1990) (see fig. 10).

The point where the old toe may have emerged is about 430 meters upslope from the currently active toe. Crandell and Varnes (1961) dated the reactivation at 300 to 350 years. Measurements of control lines carried out by Baum and Fleming in 1990 and 1991 show rate of movement of 1.35 meters per year at this part of the landslide (unpubl. data, 1991). Thus, the position of the currently active toe is about where it should be, given the speculated point of emergence, rate of movement, and age of sliding.

The thickness was outlined on the basis of the depths obtained from the flux model. Between computed points, the failure surface was drawn roughly parallel to the topography, on the basis of the information coming from the general trend of surface features mapped in the summer of 1991. As previous studies have shown, there is a correlation between slide thickness and surface areal strain: areas of contraction are generally associated with thickening, whereas areas of dilation are associated with thinning (Lantz, 1984).

Given all these assumptions and uncertainties, the volume of the active landslide was measured to be 19.5×10^6 m^3. This result is very tentative primarily because we had no direct information on thickness of the landslide anywhere along its length. The small value is only about twelve percent of the total landslide volume. The result is surprising and not presented with great confidence.

STRENGTH ESTIMATION

The old Slumgullion landslide at its toe and where it blocked the Slumgullion Creek (fig. 1) created a snout-like feature similar in form to the terminus of a lava flow or glacier. Other investigators, most notably Nye and Johnson, have used the shape of the terminus to compute a yield strength. The yield strength is a simple parameter representing a perfectly plastic material.

Observation of current movement of the Slumgullion landslide reveals that the movement is not completely distributed plastic flow; nearly all the movement is through sliding and internal shearing on well defined surfaces (Guzzi and Parise, 1991). Whether there is distributed deformation deep within the landslide, as would be produced by plastic or viscous flow is unknown at this

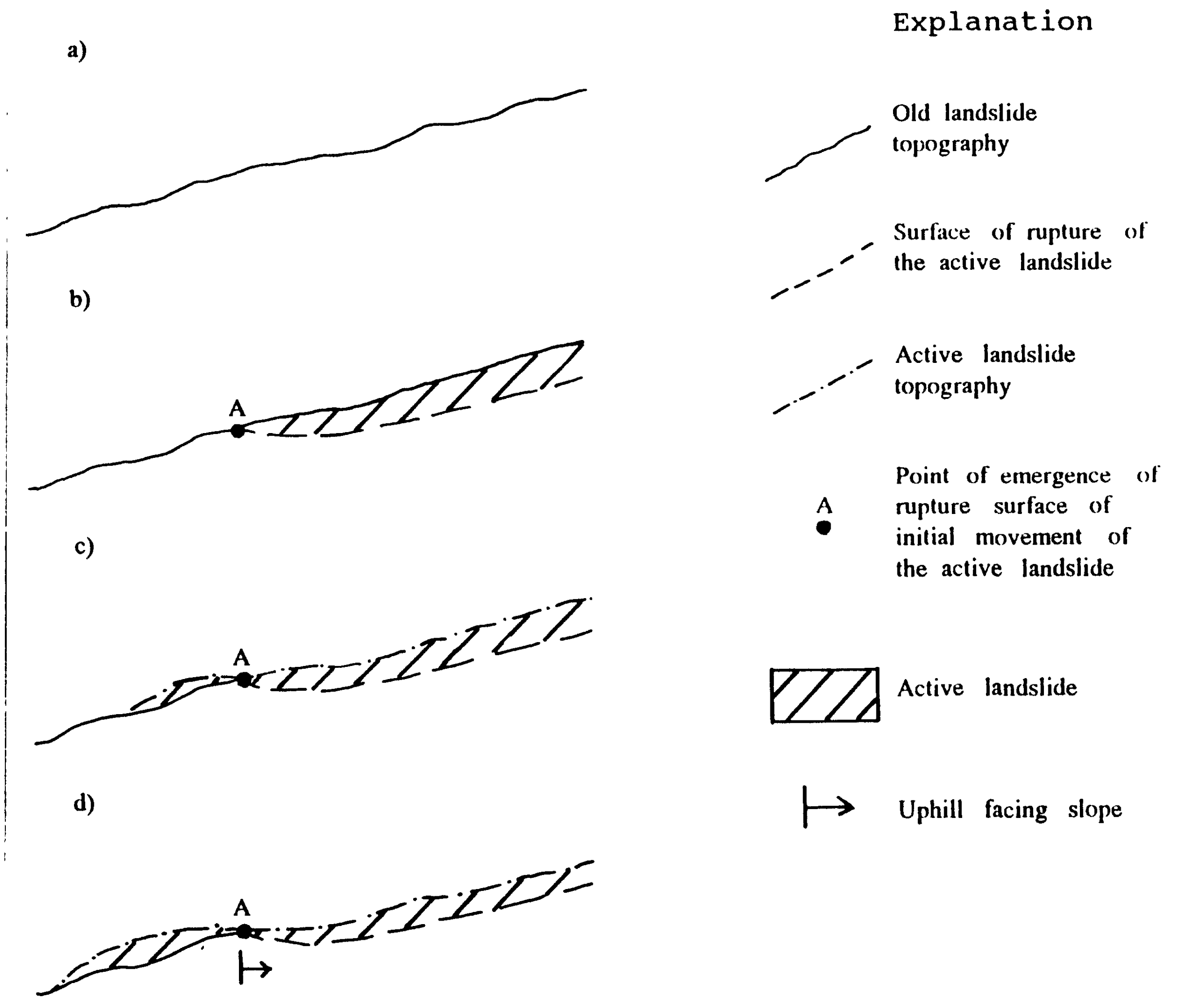

Fig. 10 - Sketch showing successive phases of developing of the toe of the active landslide's area.

a) Pre-active landslide situation: The slope topography is the result of the old landslide, already occurred.
b) Beginning of the remobilization: Part of the old landslide material begins to remobilize, forming the younger and still active landslide. Point A is the toe of surface of rupture of the active landslide.
c) Continuation of the movement: Part of the material flows above the old landslide topography, downhill of point A. As the material continues to move, the foot of the active landslide increases in thickness.
d) Present situation: The landslide is still active; its foot is moving above the old landslide topography. Point A, marking the emergence of surface of rupture of the active landslide, is presently indicated by the backward dipping of layers of sediment.

time. Measurements currently being made by the U.S.G.S. will document the amounts of surficial deformation of different types.

Nonetheless, the old Slumgullion landslide has the appearance of a flow and the terminal snouts are usable for analysis using the method of Nye and Johnson. In this part, we first describe the methods and then apply them to estimate the yield strength of the old Slumgullion landslide.

A perspective

Nye (1951, 1952b) considered the quasi-static equilibrium of an ice cap of irregular shape resting on a horizontal bed, approximating the ice behaviour to a plastic material. He derived the following equation for the snout of the terminus of the ice profile:

$$h=\sqrt{2h_o s} \qquad (1)$$

where s is the distance from the lower edge of the snout taken along a line of flow, and

$$h_o=\frac{k}{\rho g} \qquad (2)$$

where k is the yield strength, ρ is the density and g is the acceleration due to gravity.

From these two equations it is possible to estimate the yield strength of the material, knowing its density, the height h of a point along the curving snout, and the distance s of that point from the toe. The value for k is given by:

$$k=\frac{h^2\rho g}{2s} \qquad (3)$$

Johnson (1970) derived a similar expression for the terminus of debris flows. Assuming that the debris flow material is a rigid-plastic substance (angle of internal friction $\varphi=0$), and that the snout surface is in critical equilibrium and meets the horizontal surface vertically, he described the shape of its profile in the snout region with the equation:

$$x=-\frac{2k}{\gamma_d}\ln[\cos(\frac{\gamma_d}{2k}y)] \qquad (4)$$

where x and y are the horizontal and vertical coordinates of the curve that describes a profile of the snout; k is the yield strength; γ_d is the unit weight (density times gravity) of the debris.

He defined the snout height H_s as the vertical distance from the surface on which the plastic is flowing to the place where the uniform slope behind the snout breaks off to form the curved snout itself. Knowing the snout height, one may estimate the yield strength of the material by the equation

$$k=\frac{H_s}{\pi}\frac{\gamma_d}{[1-(\frac{\delta}{90})]} \qquad (5)$$

where δ (degrees) is the angle of inclination of the uniform slope behind the snout.

The equation (5) was applied experimentally on material from a debris flow on Surprise Canyon alluvial fan, Panamint Valley, California; the calculated yield strength was 3×10^3 dyne/cm^2, with a density of 2.2 g/cm^3.

Cowan and Mansfield (1970) used equation (5) to calculate shear strength for serpentinite flows in southern California. With values of density from 2.4 to 2.5 g/cm^3 they computed yield strengths varying from 0.8 to 3×10^6 dyne/cm^2. They also pointed out that the so-determined strength is identical to the cohesive shear strength τ_c in the Coulomb equation:

$$\tau=\tau_c+\sigma_n\tan\varphi \qquad (6)$$

where τ is the shear stress, σ_n the normal stress on a shear plane and tan φ the coefficient of friction. In the case of a material that actually has a friction angle ≈ 10°, the value of k calculated with equation (5) would be ≈ 30% too high, because the equation assumes the angle of internal friction to be zero (Cowan and Mansfield, 1970).

Application to the Slumgullion landslide

Assuming the angle of internal friction of the Slumgullion material as negligible at the time of flow, we applied equation (5) to estimate the yield strength of the old Slumgullion landslide material. Five profiles were drawn, two along the inactive toe, respectively going upstream and downstream in the Lake Fork valley, and the other three in the area where Slumgullion Creek was blocked.

Equation (5) is valid for material that moved on a horizontal surface. Underneath the toe of the Slumgullion landslide, the gradient of the buried topography of Lake Fork valley is very gentle; we assumed it to be horizontal, in order to use the equation. At Slumgullion Creek, the landslide moved up the valley on slopes of 8 to 14 degrees in the course of blocking the drainage way (fig. 6).

We modified equation (5) to relate the height of the snout to the angle of inclination θ of the topography underneath it (fig. 11). The modified equation is:

$$k=\frac{H\gamma_d}{\pi\left[1-\left(\frac{\theta}{90}+\frac{\delta}{90}\right)\right]} \qquad (7)$$

where H, that is, the perpendicular to the underlying topography from the place where the uniform slope behind the snout breaks off to form the curved snout itself, represents the height of the snout.

Calculated values of yield strength, based on reasonable ranges in the density of the landslide material (1.4 - 1.6 g/cm^3), vary from 2.54 to 2.75 x 10^6 $dyne/cm^2$ at the toe, and from 4.75 to 5.43 x 10^6 $dyne/cm^2$ at Slumgullion Creek.

Johnson (1970) found that for debris flows it is possible to have differences of an order of magnitude between the values of the yield strength estimated in the snout region and those in the interior of the debris flow. This because the equation (5) does not take into consideration the influence of important factors as the moisture content, the internal friction, and the concentration of the coarser material in the snout region.

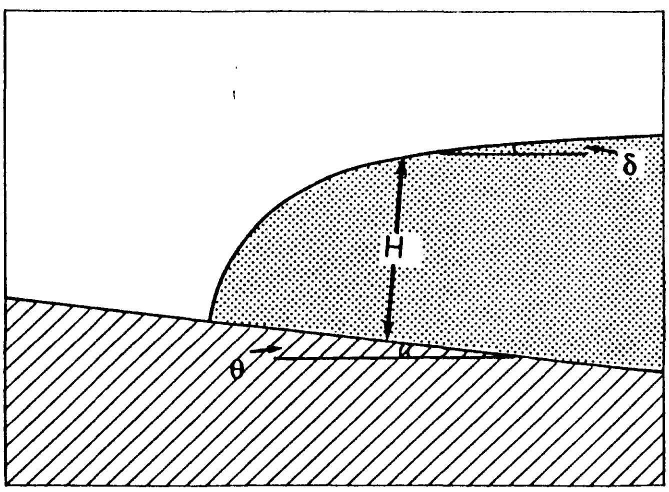

Fig. 11 - Idealized cross section through the snout of a rigid-plastic substance in critical equilibrium (after Johnson, 1970). H = snout height, δ = angle of inclination of the slope behind the snout, θ = angle of inclination of underlying topography.

Johnson (1970, p. 457) concludes that "strengths estimated by measuring snout heights will tend to be high values for the debris".

For the Slumgullion landslide, on the contrary, the value on the toe is about half of the value estimated in the area where the old Slumgullion Creek was blocked.

A possible explanation could be that the material in the toe region was remobilized at least once after the first event, and attained its present position only after successive movement(s). The remobilization would have caused a reduction in strength, and therefore the difference observed with the values at the interior of the landslide.

This hypothesis is suggested by the height of the external flank ridges that bound the landslide; they were presumably formed during the first stage of movement. The flank ridges usually observed in landslides are formed by deposition or by deformation of landslide debris; they are generally from tens of centimeters to few meters high above the moving material (Zaruba and Mencl, 1982; Fleming and others, 1988; Fleming and Johnson, 1989).

The height of the external flank ridges at the Slumgullion landslide, as much as 40 m above the adjacent currently active material (Guzzi and Parise, 1991), seems then very strange. Probably other landslide material was originally emplaced between the external flank ridges; the difference in height between flank ridges and moving ground was therefore at that time in the order of a few meters. This material was successively removed downstream during renewed or continued movement. This further movement may explain the "gap" of material between the ridges, and their present great height relative to the rest of the landslide debris.

In Table 2 the strength values estimated for the Slumgullion landslide are listed together with those of other flows mentioned above.

The strength of the Slumgullion landslide is three orders of magnitude larger than those calculated by Johnson (1970) for debris flows in California. The results for Slumgullion are comparable to the values Cowan and Mansfield (1970) reported for serpentinite flows. Considering the differences in density for the Slumgullion material (1.4 - 1.6 g/cm^3) and the serpentinite (2.4 - 2.5 g/cm^3), the strength of the landslide deposit is surprisingly large.

TABLE 2 - Strengths estimations of various flows.

Location	Type of movement	k (dyn/cm^2)	γ (g/cm^3)	Reference
Alpine valleys, Europe	glacier	0.88 x 10^6	0.88-0.92	Nye (1952a, 1952b)
Panamint Valley, California	debris flow	3x10^3	2.2	Johnson (1970), p. 445 and 457
Wrightwood, California	debris flow	6.02 x 10^3	2	Johnson (1970), p. 511
Joaquin Range, California	serpentinite flow	0.8-3 x10^6	2.4-2.5	Cowan & Mansfield (1970)
Slumgullion, Colorado	earthflow	2.64-5.09 x10^6	1.4-1.6	This paper

CONCLUSIONS

The volumes of the old Slumgullion landslide together with the currently active portion is estimated to be 160 x 10^6 m^3, based on reconstruction of the buried topography under the slide. A very tenuous estimate of the currently active portion is 19.5 x 10^6 m^3. Estimates of the yield strength of the debris, assuming a perfectly plastic material, range from about 2.5 to 5 x 10^6 dyne/cm^2.

The values here presented (thickness of landslide, volumes, strength) will be checked later on with data that may come from boreholes and from geotechnical analyses of the samples.

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