U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Surface features and kinematics of the Slumgullion landslide, near Lake City, Colorado

by

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Open-File Report 92-252

Prepared in cooperation with Italian
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1992

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SURFACE FEATURES AND KINEMATICS OF THE SLUMGULLION LANDSLIDE NEAR LAKE CITY, COLORADO

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ABSTRACT

The Slumgullion landslide, in southwestern Colorado, is a complex landslide consisting of an active landslide currently moving on the upper part of an older, larger, and inactive landslide. The inactive landslide occurred 700 years ago and dammed the Lake Fork of the Gunnison River forming Lake San Cristobal. The landslide deposit is 6.8 km long with a volume of about 170 x 10^6 m^3. The active landslide, 300 years old, is 3.9 km long and has an estimated volume of 20 x 10^6 m^3.

Scant data indicate that the fastest movement occurs near the central and narrowest part of the active landslide. The upslope one-fourth of the landslide, about 350 m wide, moves approximately 2 m/yr. The central part is about 180 m wide and moves 6 m/yr. The toe is 430 m wide and moves about 1.3 m/yr.

Surface structures of the active part of the Slumgullion landslide include scarps, strike-slip faults, thrust faults, tension cracks, flank ridges, folds, and ponds. These structures are ephemeral; the continuous movement of the landslide tends to modify or destroy them.

Transverse scarps, created by normal faults, are concentrated in the upper part of the landslide whereas longitudinal scarps, created mainly by strike-slip faults, are present in the middle to lower part. Thrust faults are evident in the downslope part of the landslide, marking a large internal toe and the limiting active toe of the Slumgullion landslide. Strike-slip faults, present as segments, bound the flanks of the entire active landslide. There are also internal strike-slip faults within the middle part of the landslide including the narrowest part. Individual segments of the strike-slip faults can be as long as hundreds of meters; en echelon tension cracks, scarps, folds, basins, and flank ridges are associated with them.

Analysis of the distribution of surface structures, and the distribution of velocities enabled us to distinguish three main kinematic zones within the landslide, going downhill from its upper part: a zone of longitudinal stretching, a zone of strike-slip faulting, and a zone of longitudinal shortening.

INTRODUCTION

The Slumgullion landslide, near Lake City, Colorado (figs. 1 and 2), has been described since the last century as one of the larger active landslides in the world (Endlich, 1876; Howe, 1909; Atwood and Mather, 1932; Burbank, 1947; Crandell and Varnes, 1960, 1961; Keefer and Johnson, 1983). In spite of this, until today it has not received detailed quantitative study, with the exception of the study by Crandell and Varnes in 1961.

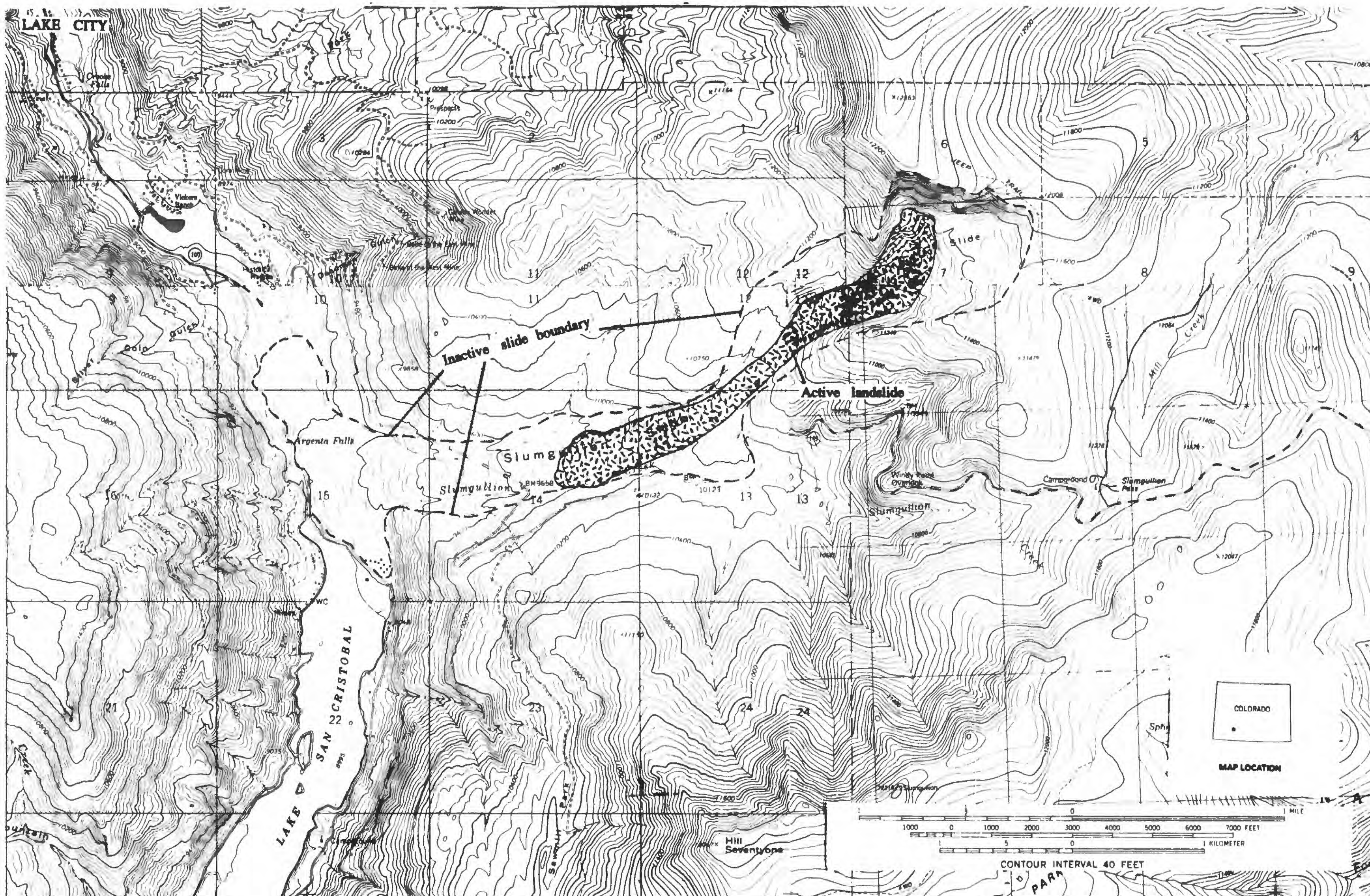

Figure 1 - Map showing location and boundaries of the inactive and active (stippled) parts of the Slumgullion landslide.

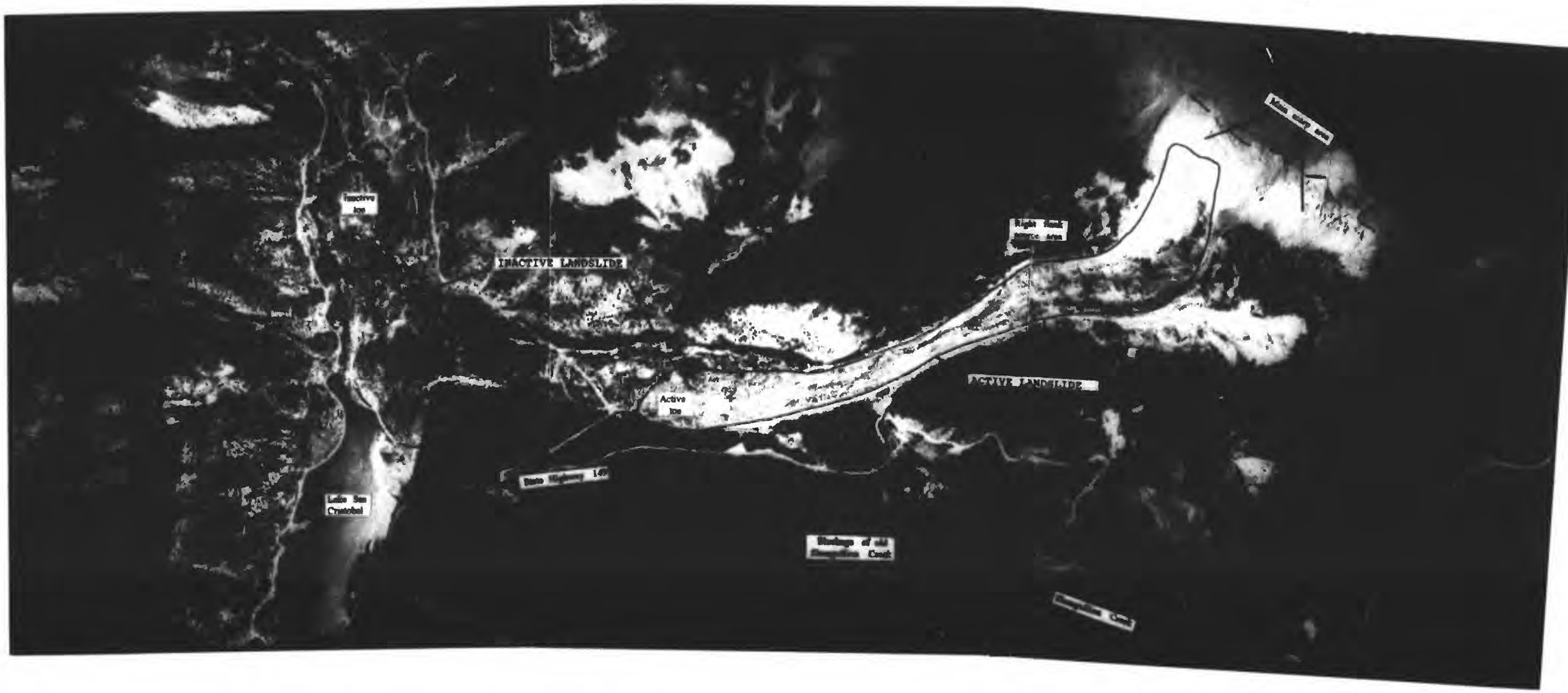

Figure 2 - Vertical aerial photograph of the Slumgullion landslide in 1990. Boundaries of active (solid line) and inactive (dashed line) parts outlined.

The landslide consists of two different parts: one part is currently active and sliding within the boundaries of the other, which is a larger, inactive landslide (figs. 1 and 2). Analysis of tree rings from the active and inactive parts of the Slumgullion landslide (Crandell and Varnes, 1960) indicate that the inactive landslide is about 700 years old and the active landslide is about 300 years old.

This paper is the second of a two-part description of the landslide. Authors, Raffaela Guzzi and Mario Parise, 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 USGS. Fieldwork was conducted during two field seasons in 1990 and 1991. The first part (Parise and Guzzi, 1991), deals principally with the reconstruction of the pre-landslide topography and the computation of the volumes of both the inactive and active parts of the landslide. In addition, the morphology of the toe of the inactive landslide was used to estimate the strength of the material involved in the landslide at the time of initial failure.

The present paper describes the distribution and geometry of the surface features of the Slumgullion landslide. We begin with a brief description of the characteristics of the older landslide; this is followed by an analysis of the available data on the rate of movement of the active landslide. Next, the surface features of the active landslide as mapped in the summer of 1991 are described in detail and discussed. Photographs and sketches of individual features are keyed to a location map (fig. 3). Finally, we analyze the kinematics of the landslide.

At the active Slumgullion landslide, weathering and erosion tend to erase prior traces of the movements so that many features are ephemeral. Another difficulty in observing and understanding landslide structures is concealment of cracks by grass, leaves, and rubble as well as interference with their formation by rocks and roots. In spite of these problems, study of the actively forming structures provides important information about the distribution of internal deformation and the kinematics.

During mapping, the distribution of vegetative cover on the landslide and its degree of disturbance provided information about the areas more affected by movement and the relative age of the movement itself. The vegetation on the Slumgullion landslide is made up of spruce, fir and aspen. The continuously active areas generally are characterized by bare ground, or at least by the presence of few trees, while in areas of fresh movement the trees show clear signs of disturbance. They have been tilted during the movement, and then grow vertically during the period of inactivity. The relative age of the movement can then be inferred by the curvatures of the trunks and by their position. The closer the curvature to the tip of the tree, the more recent is the movement. In many places, we observed trees bent in three or four places along their trunks, which indicates different stages of movement with different directions.

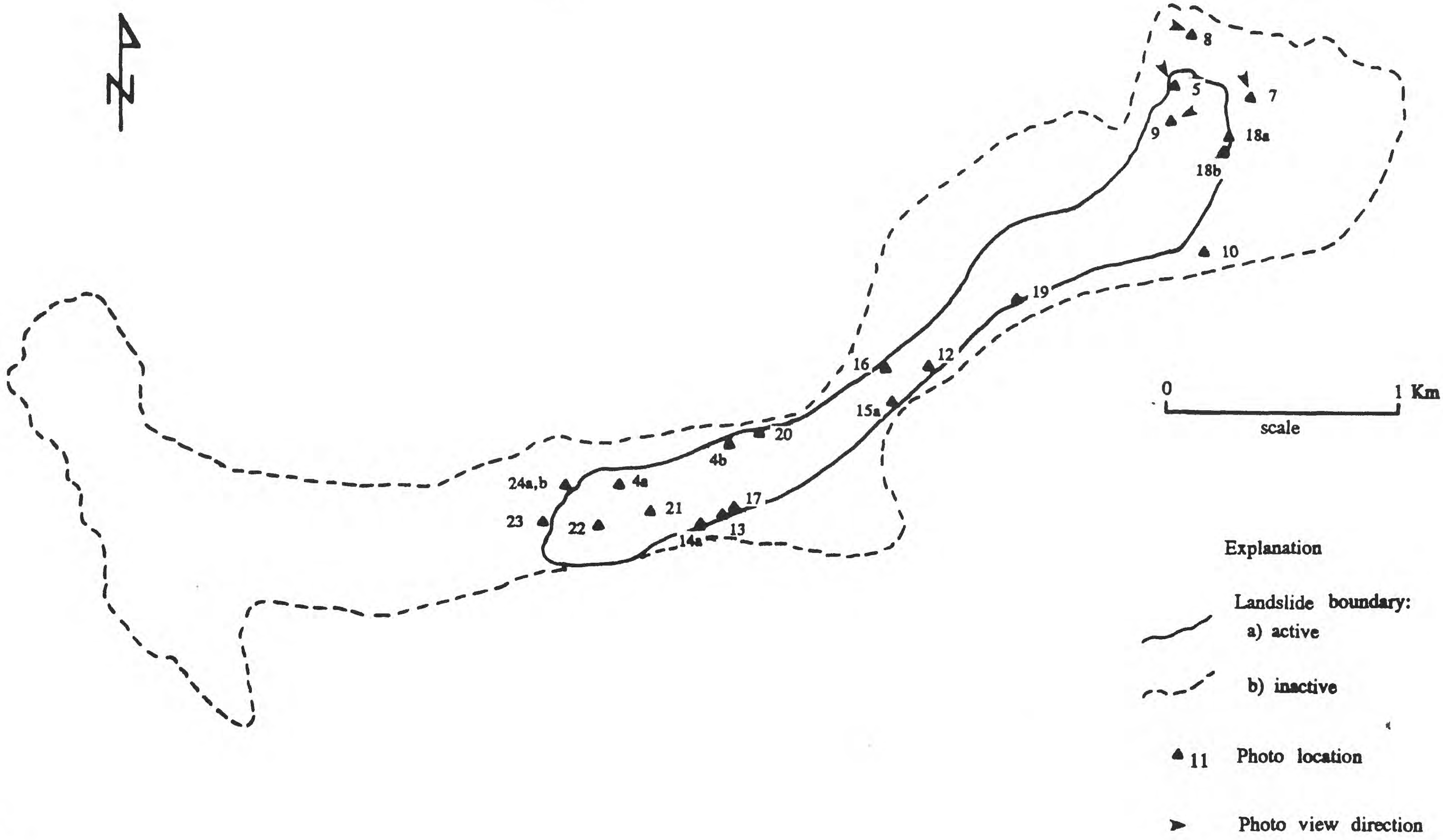

Figure 3 - Map showing location of photographs and direction of view. Numbers refer to figure numbers cited in text.

In several areas, the observation of trees on the landslide also allowed us to determine the width of tension cracks and the amount of lateral movement along shear surfaces. There are many trees split in two, three, or four parts, because they straddle active cracks (fig. 4). Often the trees, whether spruce, fir, or aspen, are still alive in spite of the breaking.

The structures created by movement of the Slumgullion landslide were mapped on a digital topographic base map prepared from aerial photographs made in 1990 (nominal scale 1:6,000). The base map was printed at a scale of 1:1,000 for field mapping. Most of the mapping was done in May, 1991, when ephemeral features were at their peak of development shortly after melting of the snowpack. Mapping was completed and field checked in June and July, 1991. Field sheets were reduced and data recompiled on a base map at a scale of 1:3,000, shown as plate 1.

In this paper, we apply the classification of mass movements of Varnes (1978) and the nomenclature for landslides suggested by the Working Party on World Landslides Inventory (WP/WLI, 1990), for the terminology of the different parts of the landslide.

Acknowledgments

The U.S. Bureau of Land Management and the U.S. Forest Service permitted access to study the landslide. USGS support was provided by David and Katharine Varnes, Robert Fleming, William and Jill Savage, Robert Schuster, Rex Baum, Richard Madole, Jean DeWoody, Philip Powers, William Brown III, and William Smith. Giovanni Crosta, University of Milan, participated in the field mapping. Sandra Natoli, University of Rome, drafted some of the figures. The topographic map of the landslide was by James Messerich. Professor Marino Sorriso-Valvo served as advisor to the study from the IRPI of Cosenza.

To these people and organizations, we express our sincere appreciation. We thank particularly Rex Baum and Robert Fleming for providing unpublished data.

GEOLOGIC AND GEOGRAPHIC SETTING

The Slumgullion landslide is located in the San Juan Mountains of southwestern Colorado, about 3 km southeast of Lake City (fig. 1). The landslide occupies the valley formed by Slumgullion Creek, a tributary of the Lake Fork of the Gunnison River. The head of the landslide is at the edge of Mesa Seco, and the toe occupies the former course of the Lake Fork.

The geologic setting of the landslide is complex. The headscarp is on the northeastern border of the Lake City caldera and contains a wide variety of rock types that have been altered hydrothermally as well as weathered (Lipman, 1976). The rocks exposed in the scarp consist mainly of volcanic tuffs and rhyolite

(a)

(b)

Figure 4 - Examples of split trees on the north side of the toe area of the active landslide: a) tree split into four parts, along a complex fault having opening and right-lateral strike-slip motion. Overall opening is 1.8 m, right-lateral displacement is 0.5 m. b) aspen tree split along a tension crack; opening is 0.7 m. For photo location, see fig. 3.

and latite flows of Tertiary age (Howe, 1909; Crandell and Varnes, 1961; Lipman, 1976). The rhyolites, phenocryst poor, formed from thick lava flows and locally include flow breccias. In places, particularly the lower part of the scarp, the rocks have been so strongly altered by the action of hydrothermal fluids that most of the minerals have been transformed to clay minerals. The principal clay mineral is montmorillonite; other minerals present in subordinate amounts as products of alteration include gypsum, feldspar, quartz and biotite (Howe, 1909; Crandell and Varnes, 1960).

Well developed badlands have formed in the altered tuffs within the landslide deposits (fig. 5). It is the presence of these bright yellow clay-rich materials, occurring together with reddish-brown volcanic rocks and local concentrations of red and purple clay-rich materials that gives the landslide its name. The term "slumgullion" refers to a type of meat stew containing several ingredients of different color and texture.

The kinds of rock and engineering soil exposed on the surface of the active landslide appear to be the same as those in the headscarp, although the quantities of each material are noticeably different. There is not as much volcanic flow rock exposed on the landslide surface as appears to be in the headscarp. Also, there appears to be less reddish-colored clay-rich material in the scarp area than on the surface of the landslide. The active landslide surface contains a preponderance of yellow to yellow-brown clayey soil with scattered patches of rock and soil including volcanic rock fragments and red, purple and white areas of clay-rich soil.

The superficial water system on the active Slumgullion landslide consists of streams with generally straight courses in sloping areas, interrupted by a meandering pattern in the flat areas. The bed material is angular and varies in size from clay to cobble; boulders are also present in the upper part of the streams. This superficial system is intimately connected with a ground-water system. Running water suddenly appears or disappears in many places on the landslide.

SHAPE AND DIMENSIONS OF THE LANDSLIDE

The 700-year-old, inactive part of the Slumgullion landslide extends about 6.8 km downhill from a scarp on the western edge of Mesa Seco to the Lake Fork of the Gunnison River (figs. 1 and 2). Lake San Cristobal formed when the toe of the old landslide blocked the Lake Fork. The Lake Fork incised a natural outlet in the landslide material and has avoided failure of the landslide dam (Schuster, 1985).

The volume for the entire Slumgullion landslide, active and inactive parts, is between 142-168 x 10^6 m^3 (table 1). The volume of the landslide was estimated at 168 x 10^6 m^3 by reconstruction of the buried topography from the exposed morphology of nearby slopes and drainage basins (Parise and Guzzi, 1991).

Figure 5 - View of the west part of the headscarp area. Note the abundance of yellow (light-colored) clay-rich material in the lower part of the scarp and the well developed badlands formed in landslide deposit in the foreground. For photo location, see fig. 3.

A second method to estimate the volume of the landslide deposit is to reconstruct the volume of material that is apparently missing from the headscarp on Mesa Seco. The volume of missing material in the headscarp is 110 x 10^6 m^3. This volume of intact rock would produce a volume of about 142 x 10^6 m^3 by bulking approximately 30 percent during the landslide process. Thirty percent is the average bulking factor generally observed in landslides (Hadley, 1978; McSaveney, 1978; Plafker and Ericksen, 1978; Nicoletti and Sorriso-Valvo, 1991).

The landslide deposit covers an area of 4.64 km^2. The average thickness of the entire deposit is about 40 m. The maximum thickness of about 140 m is in the area where the toe of the active part of the landslide has piled material over the inactive part. This point is about 250 m uphill from where Colorado State Highway 149 crosses the inactive part of the landslide (figs. 1 and 2).

The longitudinal profile of the landslide deposit is concave upward in the head, convex upward on the toe, and consists of a series of benches and ramps between head and toe (fig. 6).

The width of the old landslide deposit changes over its length (figs. 1 and 2), from 1,130 m at the head to the minimum width of 290 m at elevation of 3,180 m (10,440 ft contour line in fig. 1). The narrowing was apparently controlled by the shape of the pre-landslide valley: the topography that emerges from under the landslide deposit suggests a narrow section of the valley in this area (Parise and Guzzi, 1991). Downslope from this point of minimum width, the south side of the landslide moved laterally and upstream along the former course of Slumgullion Creek. Based on morphology of the deposits, Slumgullion Creek was blocked by the landslide, a lake formed, and lacustrine deposits accumulated (fig. 2).

Where the landslide entered the valley of the Lake Fork of the Gunnison River, it flowed both upstream and downstream creating a broad blockage of the river. The deposit occupies a length of 2,000 m along the Lake Fork channel and under Lake San Cristobal.

The active part of the Slumgullion landslide occupies much of the upper part of the inactive landslide deposits, but it covers only about 30 percent of the total area of the inactive deposits (figs. 1 and 2). The area and volume of the active part (table 1) as well as the shape of the failure surface were estimated from existing data on geometry and rate of movement of the landslide (Parise and Guzzi, 1991). The estimated volume of the active part is only about 12 percent of the total volume of the Slumgullion landslide (table 1).

The ground surface of the active landslide is very uneven and contains benches 40-50 m high separated by flatter segments over the entire length of the landslide (fig. 6). The width in the upper part varies from about 250 m to 400 m; it then decreases to a narrow section only 150 m wide at a point about 1,400 m downslope from the uppermost cracks. Farther downslope, the width increases to 430 m at the active toe (fig. 1). Because of the extreme length of the landslide, it lacks the classic "hourglass" shape of an earthflow; the length to width ratio is as large as 9:1.

TABLE 1 - Morphometric measurements on inactive and active parts of the Slumgullion landslide.

Features	Dimensions of inactive part	Dimensions of active part
Area of deposit	4.64 km^2	1.46 km^2
Length	6.8 km	3.9 km
Width		
- head	1,130 m	280 m
- narrowest part	290 m	150 m
- distal part	530 m	430 m
Relief		
- elevation of crown	3,700 m	3,500 m
- elevation of toe	2,700 m	2,960 m
Average slope		
- deposit only	7° (12%)	---
- including main scarp	8° (14%)	8° (14%)
Thickness		
- average	40 m	13 m
- average on thalweg of buried valley	90-100 m	---
- maximum	140 m	48 m
Volume*		
- landslide deposit	168 x 10^6 m^3	19.5 x 10^6 m^3
- detached mass (including a 30% bulking factor)	142 x 10^6 m^3	---
Length : width	> 6:1	9:1

* from Parise and Guzzi (1991)

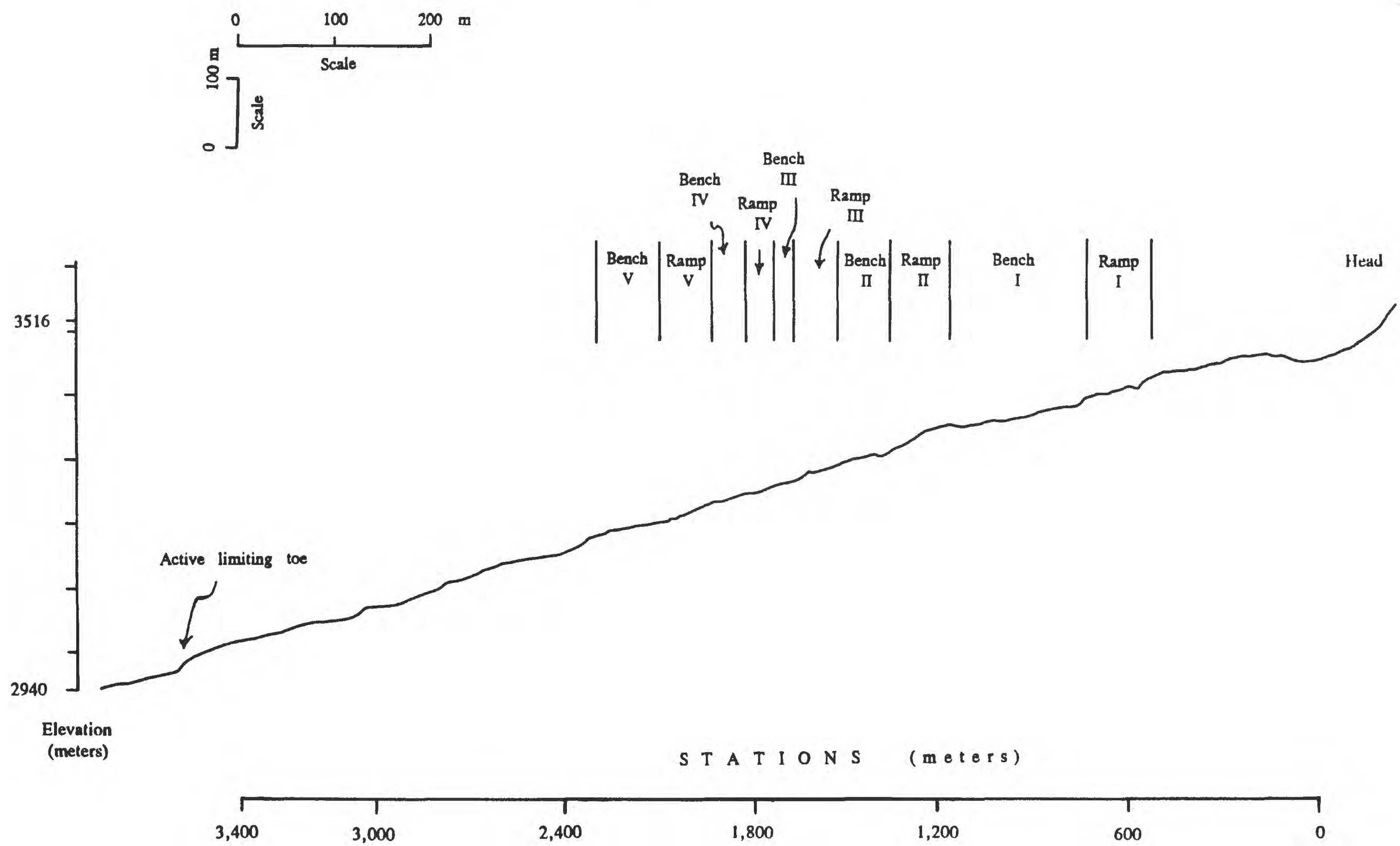

Figure 6 - Longitudinal profile of the active part of the Slumgullion landslide.

SURFACE FEATURES OF THE INACTIVE LANDSLIDE

HEADSCARP

The headscarp of the inactive landslide consists of an amphitheater about 1,200 m wide and up to 250 m high. The scarp appears to be eroded over its entire length (figs. 7 and 8). Numerous fissures and cracks in the scarp that are open as much as 20 cm indicate that the scarp is crumbling. Rock falls and topples are very frequent in the headscarp area; they feed accumulations of slope debris that are widespread at the base of the scarp. Several large talus aprons are distinguishable in figures 7 and 8. The largest talus apron, in the middle part of the scarp area, contains angular boulders as large as 7 m across (fig. 8). The lower part of the scarp as shown in figures 7 and 8 is buried by talus. The coarser part of the talus accumulates at the base of the deposit and progressively finer materials occur higher in the deposit. Here, the coarse rock fragments occur in bands that are nearly normal to the direction of movement of the main body of the landslide. Downslope, within the main body, most concentrations of rock fragments are in bands that are parallel to the direction of movement (fig. 9).

We infer that the main body of the landslide was emplaced as a result of the collapse of part of Mesa Seco in a single or few episodes of movement. If the Slumgullion landslide was the product of gradual degradation of the scarp and more or less continual incorporation of material from the talus aprons into the landslide, the coarse fragments would not be aligned in the direction of movement but rather would occur as isolated patches or bands normal to the direction of movement.

The northwestern part of the scarp is currently the most active. This area contains some relatively small active scarps and rock-fall deposits that may be adding material to the head of the currently active part of the landslide. However, our mapping of the active part of the Slumgullion landslide could not discern cracking and deformation features this far uphill. Thus, this area of activity is isolated from the larger, currently active landslide and the secondary landslide described below.

Downhill from the main scarp area, on the northwestern side of the landslide in the east part of Section 12 (fig. 1), a secondary landslide area extends from an elevation of 3,475 m (11,400 ft) to 3,170 m (10,400 ft). The main scarp of this landslide, which faces westward, is up to 350 m wide and about 100 m high. Here, virtually all the volcanic rock has been altered to a yellow clay-rich material. Several south-facing scarps up to 35 m high are developed within this secondary landslide mass. The displaced materials are partly covered by spruce and fir trees that are straight and upright. Despite the presence of the well-developed scarps, fresh cracks are absent, and the entire area is apparently inactive except for falling, rolling, and bouncing of isolated boulders on the steepest scarps and the rill and gully erosion in the

Figure 7 - View of the northwestern part of the principal scarp showing the materials involved in the landslide. For the most part, the materials are reddish-brown volcanic flow rocks and tuffs that have locally been altered to yellow or red clay. Note the accumulations of talus that cover the lower part of the slope. For photo location, see fig. 3.

Figure 8 - View of the western part of the source area, showing some of the talus accumulations at the base of the scarp. Coarser materials are concentrated in the lower part forming a bulge. The person on the boulder in the foreground gives the scale. For photo location, see fig. 3.

Figure 9 - Partially buried tongue of rock debris adjacent to a lacustrine deposit of clayey material in the head regions of the inactive landslide. For photo location, see fig. 3.

unvegetated areas. We believe that this is part of the large, inactive landslide, but the total displacement here has been much less than from the main scarp area northeast of this area. This area was included in the measurement of volume of the inactive landslide by Parise and Guzzi (1991).

FLANK RIDGES

Along the lateral boundaries of both the inactive and active landslides are linear ridges of landslide material that have formed by the movement of the landslide. These ridges, termed flank ridges, have been described for other landslides by Keefer and Johnson (1983) and Fleming and Johnson (1989). The ridges form adjacent to strike-slip faults bounding active landslides. Flank ridges have rounded cross sections. They are typically many times longer than they are wide or high; a 5-m-high flank ridge may extend continuously for several hundred meters along the edge of the landslide. The reasons for their formation and the mechanics of their growth are not clear. Nonetheless, the ridges are definitive indicators of past movement, and multiple ridges along landslide flanks are evidence for multiple episodes of movement.

At least two and probably more generations of flank ridges are distinguishable on the inactive Slumgullion landslide; they are particularly evident on the left flank in the upper part of the landslide (fig. 10) and west of the area where State Highway 149 crosses the landslide (figs. 1 and 2). The flank ridges are as much as 50 m high with respect to adjacent landslide material; from 5 to 15 m of this height is clearly the result of growth along the flank. Around much of the perimeter of the landslide, the flank ridges are fully vegetated and show no signs of disturbance by recent movement.

BODY AND TOE OF INACTIVE LANDSLIDE

About one third of the main body of the old, inactive landslide is covered by the active landslide. Features on the surface of the active part are the result of current movement. However, outside the active part, some lineations that are approximately parallel to the direction of movement are visible on aerial photographs of the lower part. Some of the lineations resemble linear features that we mapped on the active part of the landslide associated with strike-slip faults. A series of transverse steps, each as much as 30 m high, extends part way across the surface of the inactive landslide. These features might represent the remnants of shear surfaces, scarps, and internal toes that formed on the old landslide at the time of its activity; however, they have not been studied in detail.

The form and dimensions of the inactive toe indicate that it provides a buttress for the old landslide materials farther uphill.

Figure 10 - Flank ridges on older, inactive landslide formed in the yellow clay-rich landslide deposit. The boundary of the inactive landslide is out of view about 50 m to the right side of the photograph. The boundary of the active landslide is a few meters out of view to the left of the photograph. Note the difference in the height of the two flank ridges visible in this view. The larger ridge (a), on the right side may correlate with the initial failure 700 years ago, and the younger ridge (b) may record a separate episode of movement between initial failure and the currently active part of the Slumgullion landslide. For photo location, see fig. 3.

The slope of the toe at its distal part ranges from approximately 6 to 12 degrees.

RATES OF MOVEMENT OF THE ACTIVE LANDSLIDE

Crandell and Varnes (1961) provided the first data on movement rates of the active Slumgullion landslide. They studied the movement rates by measuring displacement of trees, tracking observable points on aerial photographs taken in 1939 and 1952, measuring displacements of control stakes, and by time-lapse photography. Their data are representative of about a 20-year period of movement from the aerial photographs down to day-to-day measurements by time-lapse photography. According to Crandell and Varnes (p. B136, 1961): "...the virtually constant velocity from year to year and from season to season at a given point indicates that neither long-term nor seasonal fluctuations of temperature and precipitation have much effect on movement".

Results of measurements for five points are shown in fig. 11 as reported by Crandell and Varnes (1961). The points, A-E in fig. 11, show that the rate of movement of the landslide depends on the place where the measurement is obtained. The velocity consistently increases from 0.75 m/yr at the active toe (point A) to 6.00 m/yr at the narrowest part of the landslide (point D). From there it decreases to 1.77 m/yr in the head (point E)[1].

The other displacement data were collected during our field work in the summers of 1990 and 1991. Most were obtained from a survey of selected points and lines on the active landslide and from detailed plane-table mapping by R.W. Fleming and R.L. Baum, U.S. Geological Survey, Denver, CO. The points labeled in fig. 11 from F to J provide additional data on displacement and velocity. Point F (1.35 m/yr) is on a longitudinal survey line at the active toe; point G (3.70 m/yr) is from a quadrilateral on the right flank of the landslide.

Points H and I are striped posts installed by unknown parties in transverse lines across the lower part of the landslide. The posts probably were installed in conjunction with a public information sign at a landslide overlook on State Highway 149. They are mentioned on the sign and are visible from there. Posts were placed on nonmoving ground on both sides of the landslide to create a baseline. A line of posts was installed on moving ground on the baseline in approximately 1972, and two posts remain in place on this line. A second line of posts was installed on moving ground on

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[1]The location of point E was described by Crandell and Varnes (1961) as "trees at a point 3,000 feet from the head". The location shown on fig. 11 is approximate, and its position as shown should be regarded with caution.

Point	Average velocity (m/year)	Period of measurement (years)
A	0.75	1958-1961
B	2.60	1958-1961
C	4.64	1958-1961
D	6.00	1958-1961
E	1.77	1939-1952
F	1.35	1990-1991
G	3.70	1990-1991
H	2.90	1990-1991
I	2.60	1990-1991
J	2.25	1929-1991

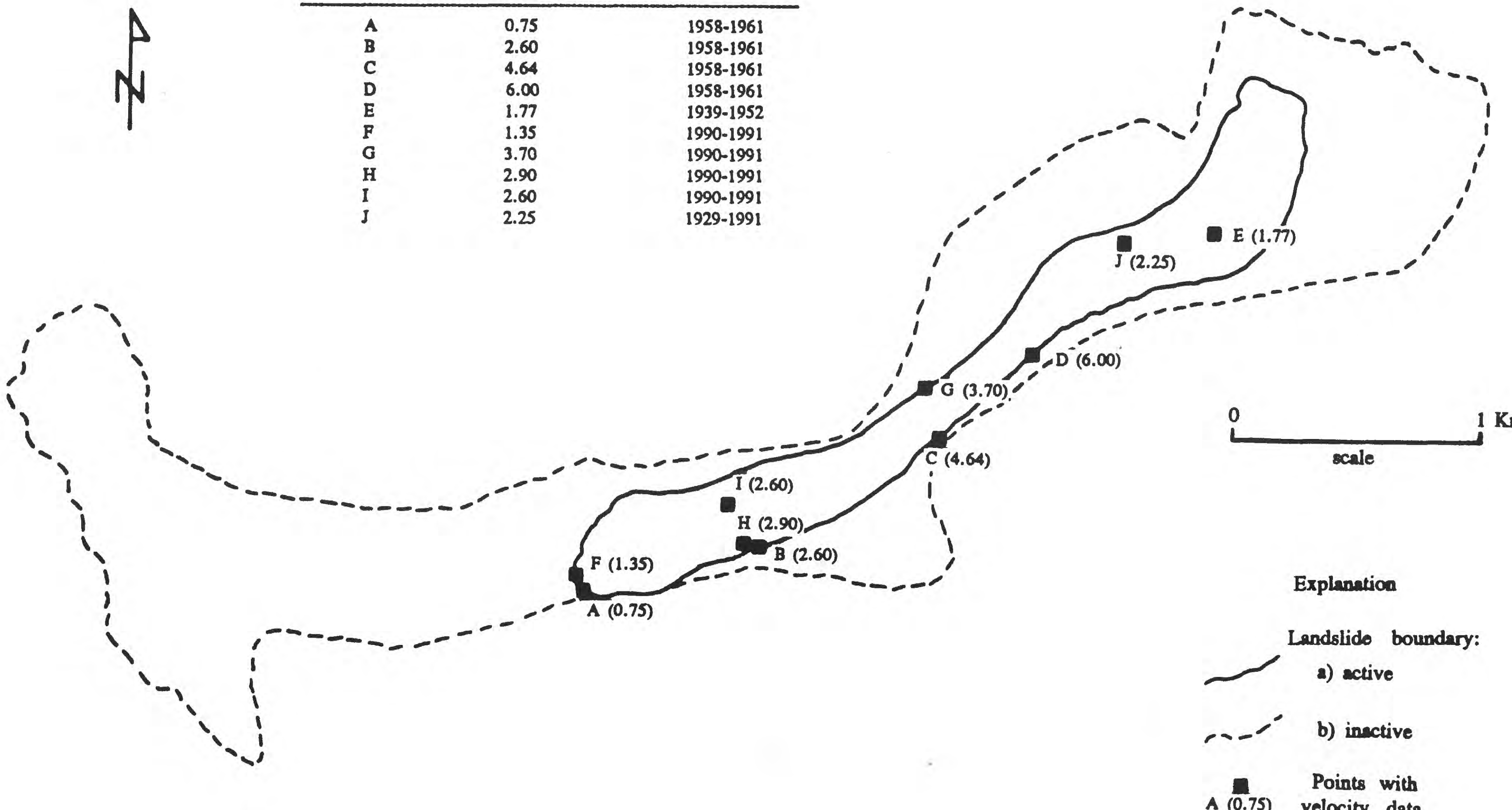


Figure 11 - Map showing locations of points where rate of displacement has been measured. Points A-E from Crandell and Varnes (1961); points F to I from unpublished data of Baum and Fleming. Point J is the U.S. General Land Office bench mark that was established in 1929. Amounts of landslide velocity shown.

the baseline in approximately 1976 after the first posts had moved off the baseline. Again, two posts could be located from this second line. One other post was found lying on the landslide surface that obviously had been disturbed and was not surveyed. Positions of the posts were surveyed in August 1990 and May 1991. The displacements of points H and I (fig. 11) from 1990 to 1991 were used to calculate the rates. Displacement at H and I is 2.90 and 2.60 m/yr respectively. The total displacements from the baseline were used with the rates to estimate when the two different sets of posts were installed.

The last point of known displacement, J, is at a bench mark installed in 1929 by the U.S. General Land Office. Records for the bench mark indicate that it was installed on the midpoint of the east side of Section 12 (fig. 1). Note on fig. 1 that there is some ambiguity about the exact point that might have been chosen to set the bench mark because there is an adjustment of the section line there. In the field, the bench mark was strongly tilted and sticking out of the ground about 0.30 m, but this type of disturbance would not be unusual for a point that had been displaced more than 120 m. Thus, we believe that the present position of the bench mark is only due to movement of the landslide. The estimated amount of movement, 2.25 m/yr, provides a 62-year record of movement, but uncertainty about the initial location of the bench mark diminishes its value.

The data from Crandell and Varnes (1961) and those collected in 1990 and 1991 are very similar. The estimates of velocity are approximately the same; the largest difference is at the active toe (points A and F, fig. 11). We do not know whether the difference there indicates an acceleration of movement in the toe or is simply a result of measuring in two different places.

At the Slumgullion landslide, the maximum displacement rate is at the narrowest part of the landslide. Displacement rates decrease both uphill and downhill from there. Displacement on the flanks (e.g. points A through D) is less than displacement a few meters inside the flanks (Crandell and Varnes, 1961). Note the difference of 0.30 m/yr between point B, which represents displacement across the flank, and point H, which is 20 m inside the flank.

Overall, the results are in agreement with the distribution of deformation observed in other landslides. The upper part of the landslide is generally characterized by stretching, the lower part by shortening, and the maximum displacement occurs somewhere between the head and toe (Lantz, 1984; Baum and others, 1989; Baum and Fleming, 1991).

Downhill from the narrowest part of the landslide at point D, the displacement rate is smaller on the north or right side of the landslide than on the south side. We lack data to determine any difference in displacement across the landslide uphill from the narrowest part. At the narrowest part, data of Crandell and Varnes (1961) show that the maximum displacement is about midway across the landslide, and the displacement on the north or right flank was slightly larger than on the south flank. Crandell and Varnes (1961) ascribed the difference in velocity at the middle of the landslide at point D to viscous flow, which is contrary to their preliminary data that indicated block movement on a bounding slip surface without internal deformation (Crandell and Varnes, 1960). The maximum difference in velocity across the surface of the landslide at location D (fig. 11) is about 0.75 m/yr where the total displacement is 6.00 m/yr. Thus, about 12 percent of the maximum displacement is due to internal deformation. Eighty-eight percent of the deformation is due to displacement as a plug with deformation concentrated on the boundaries. Whether the 12 percent deformation is distributed through the slide mass as flow or occurs on separate faults of small displacement is unknown.

DESCRIPTION OF STRUCTURAL FEATURES ON THE ACTIVE SLUMGULLION LANDSLIDE

For all except the most simple forms of slope movement, displacement by sliding produces internal deformation in the landslide mass. Each part of a landslide is generally characterized by different types and orientations of structures (Sowers and Royster, 1978; Varnes, 1978; Zaruba and Mencl, 1982). The rate and type of movement, material properties, and boundary conditions as well as initial and changing stresses interact in complex ways to produce complex structures. Areas with simple structures that are related to only a single type of deformation are rare on a large, complex landslide such as Slumgullion.

The kinds of stuctures that were observed and mapped on the landslide surface include scarps, thrust faults, strike-slip faults, tension cracks and cracks of indeterminate origin. Ponds, small landslides within the larger landslide, folds, springs, and areas of uphill-sloping ground also are represented on the map.

SCARPS

Scarps are steep slopes from a few centimeters up to tens of meters high. In general, they are the most difficult features to interpret on the landslide surface. Scarps are commonly associated with normal faults, which also produces stretching of the landslide. On the Slumgullion landslide, however, scarps take many forms and apparently are the product of several different types of differential movement. There are specific places on the landslide where scarps can be shown to be the product of thrust faulting, strike-slip faulting, normal faulting, and local erosion accompanied by ravelling or collapse of small channel walls.

THRUST FAULTS

Thrust faults are compressional structures characterized by overriding movement of one plate over another; they are mostly oriented normal to the direction of movement. Thrust faults generally occupy only part of the total width of the landslide. The overriding plate of a thrust fault is characterized by the presence of a steep frontal slope with sets of scarps and subordinate radial tension cracks; transverse tension cracks are common in the back.

A bulge often forms in the frontal zone because of the compression and of the accumulation of new material; it is then common to have a gently uphill-facing slope in the rear area, with stagnation of water and formation of ponds. An example of a thrust fault in the vicinity of the left flank of the landslide is shown in fig. 12.

STRIKE-SLIP FAULTS

Right-lateral and left-lateral strike-slip faults bound the right and left sides, respectively, of the active part of the Slumgullion landslide. Their strikes are generally parallel to the direction of movement, so that both the boundary faults strike about southwest in the upper part and west-southwest in the lower part.

At Slumgullion, the strike-slip faults form cracks from 0.05 to 0.3 m wide and few tens of centimeters deep. The faults are typically bounded by a zone of disturbed material with average width of 0.5 m (fig. 13). The strike-slip faults may be accompanied along their length by scarps ranging in height from a few centimeters to meters. Features characteristic of strike-slip faults elsewhere, including fault segments (Segall and Pollard, 1980; Deng and others, 1986; Sylvester, 1988), steps with associated compressional or extensional structures (Freund, 1974; Aydin and Nur, 1982; Mann and others, 1983), en echelon tension cracks (Freund, 1974; Segall and Pollard, 1980; Pollard and others, 1982; Deng and others, 1986; Sylvester, 1988), and en echelon folds (Fleming and Johnson, 1989) are also present at the Slumgullion landslide.

Figure 14 shows an example of the association of tension cracks, thrust faults and folds within the left-lateral strike-slip fault zone that bounds the left flank, at station 2,800 m. En echelon tension cracks are oriented with angles from 35° to 55° counterclockwise from the main shear surface (parallel to the long side of the photograph). The cracks are as much as 6 cm wide near midlength; maximum length is about 40 cm. Some of the cracks bifurcate at their terminations. Folds and thrust faults show two different trends. Folds are at right angles to tension cracks, while thrust faults make an angle of about 50° with the en echelon cracks, i.e. about 25° counterclockwise from the strike-slip fault.

Another example of the association between en echelon cracks and thrust faults in the vicinity of a left-lateral strike-slip fault within the landslide, at station 2,000 m, is shown in figure 15.

Figure 12 - View of small thrust fault (a) at edge on a dry pond, looking upstream along the left flank. The thrust fault is about 15 m wide and does not present a steep scarp in its frontal part. For photo location, see fig. 3.

EXPLANATION

Strike-slip fault, dashed where subdued (arrow in the sense of movement)

Thrust fault (teeth on overriding plate)

Tension crack

Narrow crack

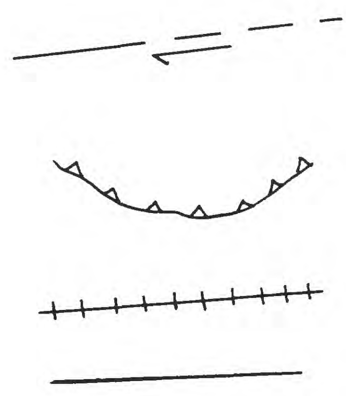
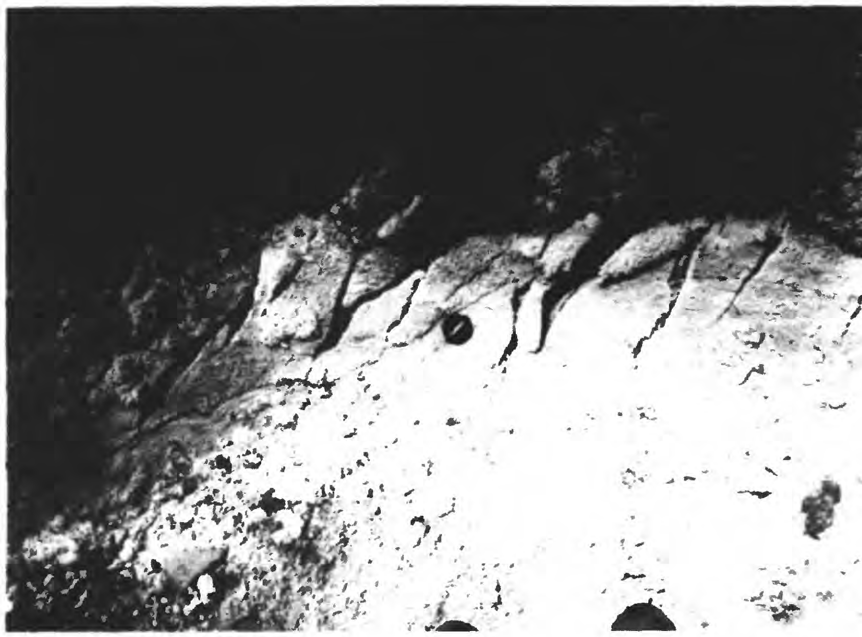
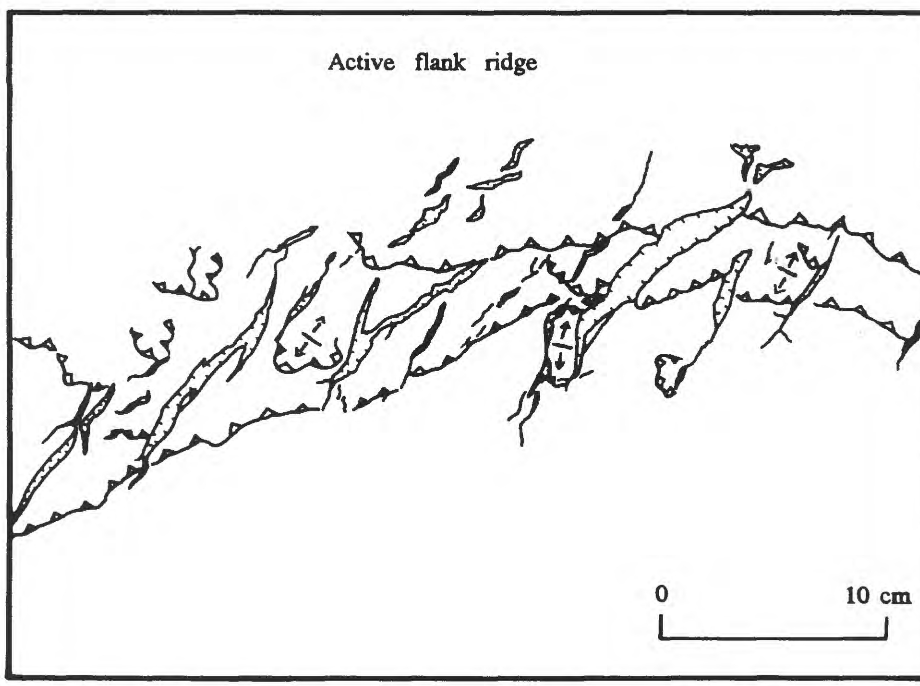


Figure 13 - Detail of the fault zone on the left flank of the landslide. The trace of the left-lateral strike-slip fault and the associated set of en echelon cracks are highlighted. In the middle of the photograph, the ground is broken by en echelon tension cracks, and the course of the strike-slip fault is not clearly defined. The field board, on the upper right corner of the photograph, is about 1 meter in height. For photo location, see fig. 3.

(a)



(b)



EXPLANATION

Open crack

Narrow crack

Thrust fault, teeth on overriding plate

Fold

Figure 14 - Association of en echelon tension cracks, folds and thrust faults in the vicinity of the left-lateral strike-slip fault bounding the left flank of the active landslide. Fig. 14b is a sketch made from the photograph. The course of the strike-slip fault is parallel to the long side of the photograph; the dark material at the top of the photograph is part of the active flank ridge being formed. Lens cap is 5.2 cm in diameter. For photo location, see fig. 3.

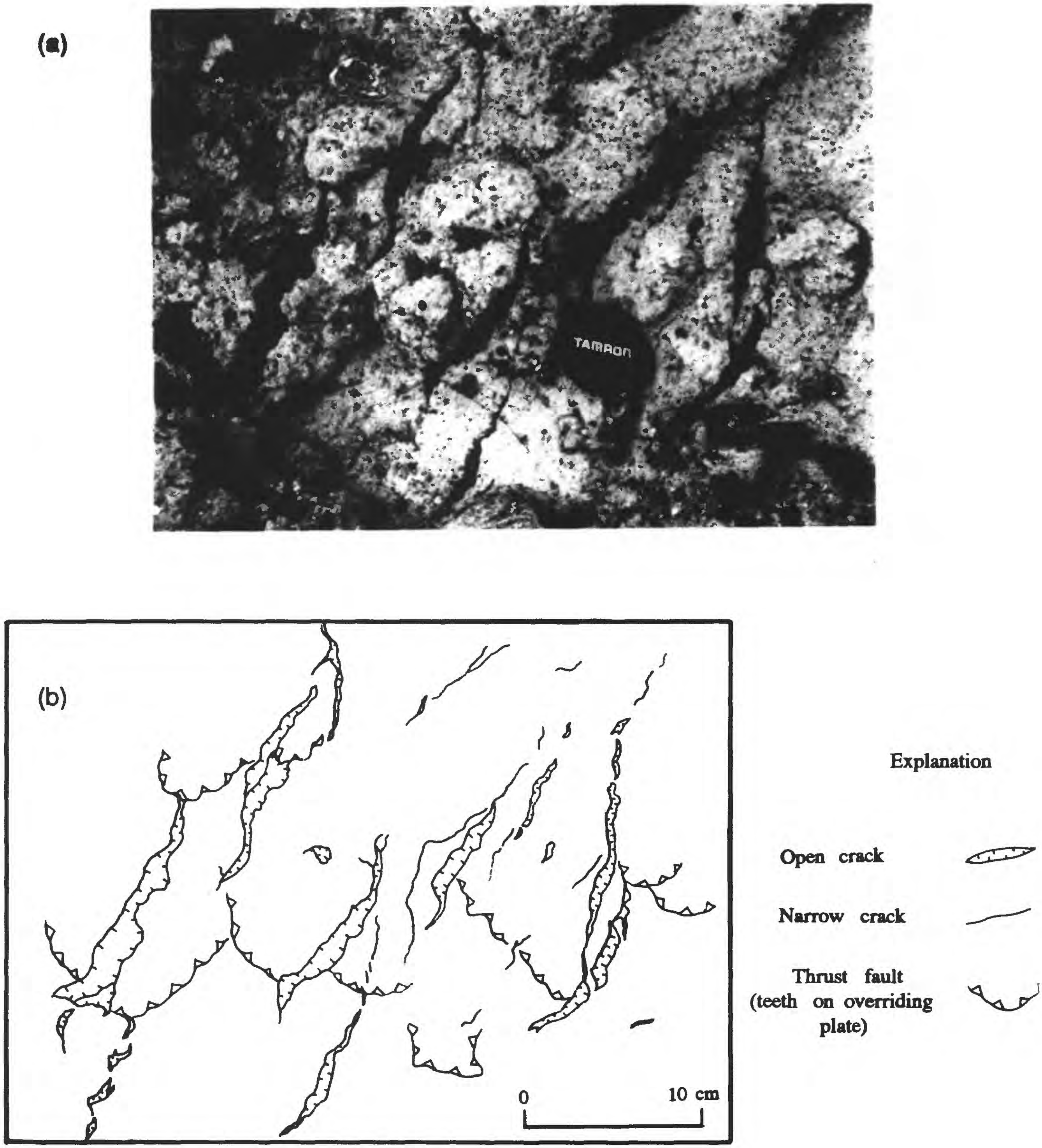


Figure 15 - En echelon tension cracks and thrust faults associated with a left-lateral strike-slip fault on the left flank of the active landslide. The course of the strike-slip fault is parallel to the long side of the photograph. Fig. 15b is a sketch made from the photograph. The cracks present both simple and sigmoidal shapes, with maximum width occurring at their midlength, and with length several times greater than the width. Lens cap is 5.2 cm in diameter. Thrust faults are generally at right angles to the cracks. For photo location, see fig. 3.

BASINS

Basins are depressions produced by steps or curves along a strike-slip fault. They form at left steps in left-lateral strike-slip faults and at right steps in right-lateral strike-slip faults (Freund, 1974; Aydin and Nur, 1982; Sylvester, 1988; Fleming and Johnson, 1989).

The basins typically are parallel to the strike-slip fault, with length as much as 10 times greater than the width. They are limited on two sides by strike-slip fault segments and on the other two sides by oblique normal faults. The normal faults make an angle from 30° to 50° with the shear zone. The basins are sometimes closed and contain ponds or they may have flattened gradients and receive large amounts of sediment. An example of a basin associated with a strike-slip fault is shown in figure 16. The basin is located on the right flank just downhill of a right step in the right-lateral strike-slip fault.

Basins have been observed also in areas some meters distant from the main shear zone. They are generally associated with fault segments. We observed that, if the fault segments make an angle greater than 20° with the strike-slip fault, the basins are wider than they are narrow; whereas, if the angle is ≤ 20°, and especially if it is almost parallel to the shear zone, the basins are several times longer than they are wide.

FLANK RIDGES

The flank ridges are commonly the best preserved feature of active landslides of the flow type. Keefer and Johnson (1983) distinguished three different ways ridges can form at the flanks of an earthflow; Zaruba and Mencl (1982) and Fleming and others (1988) used the height of the flank ridges to estimate displacement of landslides. Fleming and Johnson (1989) distinguished ridges formed by deposition from those formed by deformation of landslide debris. They also surveyed the growth of flank ridges and the development of structures associated with them.

On the active part of the Slumgullion landslide, several generations of ridges are present, both on the flanks of the landslide and within it. Some of them are actively growing, as the freshness of the exposed debris indicates.

In plan view, the flank ridges are elongate, are curved convex downward at their termini, and are generally symmetric. The axes of the flank ridges follow generally the curvature of the boundaries of the landslide, that is, of the strike-slip faults limiting them. Their course can be continuous for long distances, up to hundreds of meters, or it can be discontinuous so that the ridge is formed by several segments. The width is always very small with respect to the length. Height of the ridges ranges from tens of centimeters to 30 m. In transverse profile, the flank ridges show a convex-upward curve and V-shaped troughs on either side; the shape is then

(a)

(b)

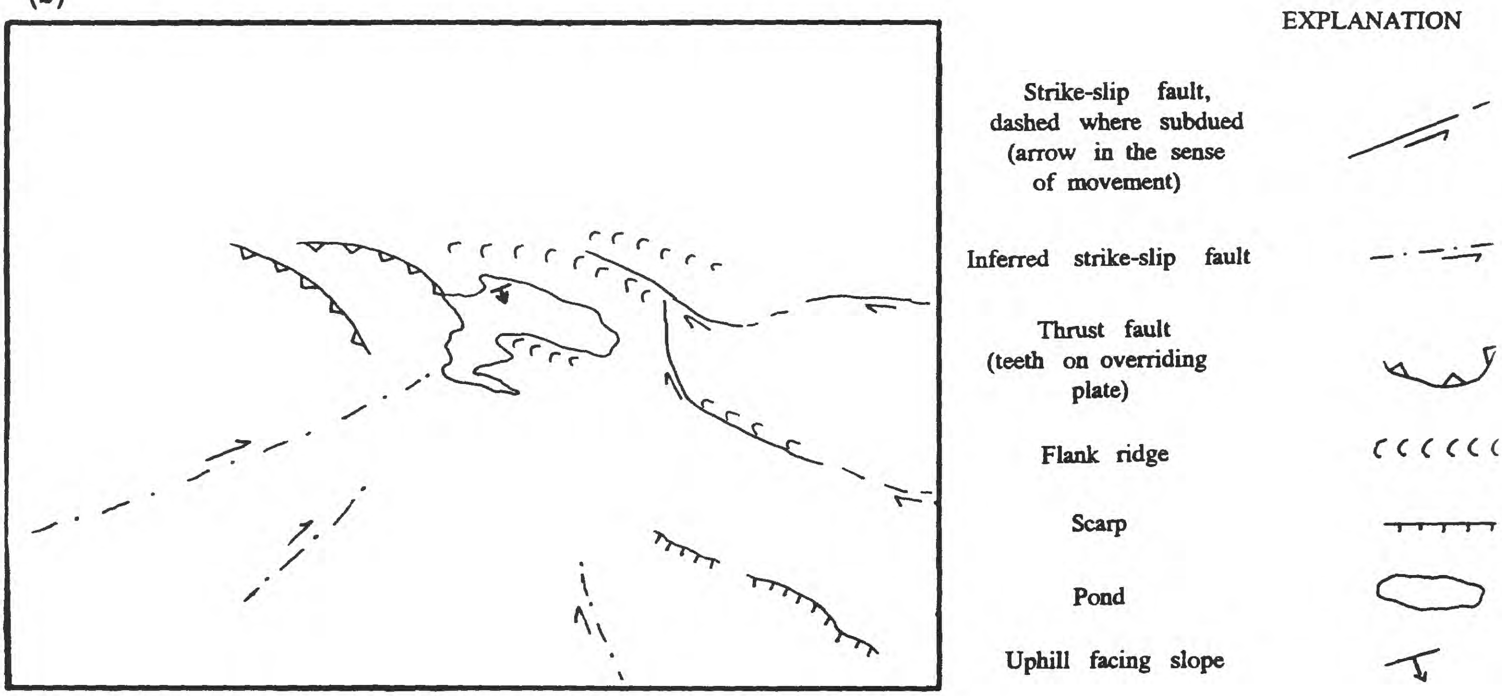


Figure 16 - a) Downhill view of basin on the right flank caused by right bend in strike-slip fault. b) Sketch of features visible on the photograph. The basin is being filled by material entering the basin through a complex system of right-lateral strike-slip faults and thrust faults. For photo location, see fig. 3.

generally rounding if height and width are comparable. With increasing height, narrow ridges with steep slopes on both sides form; for example, very narrow flank ridges are on the left flank of the landslide, between stations 500 and 800 m (plate 1), with height up to 8 m.

The ridges closer to the boundaries of the landslide are generally parallel to each other, and in turn to the strike-slip fault. In some cases the orientations are slightly convergent, reflecting local variations in the direction of movement, and (or) the developing of minor shear surfaces not parallel to the main one. In other cases, the ridges are parallel to each other, but they form an angle with respect to the shear surface, that crosses them. For instance, going down on the left flank of the landslide, from station 2,600 m downhill (plate 1), following the strike-slip fault marking its boundary, it is necessary to pass continuously from one ridge to another, stepping left, because of their orientation at an angle of about 30° with respect to the strike-slip fault. In this area the flank ridges are generally of small size, up to 2 m high and up to 1.5-2 m wide.

There is a large contrast between the sizes of the older ridges and of those that are currently active (fig. 17): the inactive ridges are generally much larger, up to 20-30 m high. Those on the extreme outside of the landslide are the largest and, based on the size of the trees and the development of soil, appear to be the oldest. They probably formed during the initial movement of the landslide. Other successive phases of movement or perhaps continual movement of a gradually decreasing volume of material led to the building of new ridges within the older and larger ridges.

The flank ridges are commonly characterized by the concentration of the coarser material in their upper part, forming the typical armoring that probably indicates upward transport. When very narrow ridges are formed, the coarser material is also present on their sides. The trees on the ridges are generally tilted toward the outside on both the sides.

The armoring is clearly visible where the left external ridge starts, at station 200 m (figs. 18 a and b). The ridge is oriented about north-south in its upper part and then follows a tight bend toward the right; it is continuous for some tens of meters downhill of the pond present on its left side. After the large bend the landslide makes toward the right, other ridges are distinguishable on the left side, oriented about east-west. They have different heights and a general trend parallel to the strike-slip fault, which extends usually on the inner side of the presently active ridge. An example of one of the minor ridges present in the area is shown in fig. 19: the ridge is 3 m high, about 5 m wide, and 12 m long.

On the right flank of the landslide, the flank ridge adjacent to the active landslide is typically continuous or segmented into shorter ridges. The ridges are largely undeformed except at a right step that widens the landslide from about 230 m to 275 m, at about station 2,500 m (plate 1). There, the ridge is broken by many

Figure 17 - Comparison between active flank ridge in the foreground and inactive flank ridge in the background, on the left flank of the landslide. The left-lateral strike-slip fault marking the boundary runs on the inside of the active ridge. Height of the active ridge is 0.4 m; height of the inactive ridge is 5 m. For photo location, see fig. 3.

(a)

(b)

Fig. 18 - Upper part of the left flank of the active landslide: a) looking uphill; b) looking downhill. The prominent flank ridge extends from the distal part of the largest rock-debris apron present in the source area. A pond has formed outside the flank ridge where it curves to the right. Note the concentration of coarser material and boulders at the top of the ridge. Farther downslope, such coarse material is much less common. For photo location, see fig. 3.

Fig. 19 - Old remnant of a flank ridge on the left side of the active landslide. The trace of the old, inactive ridge is not continuous, but consists of several small fragments of different lengths and sizes. The main fault is in the small channel in the middle of the photograph. Non-moving ground on the left side of the photograph, moving ground on the right. The active flank ridge is out of view to the right. For photo location, see fig. 3.

Fig. 20 - View of flank ridge on the right side of the active landslide that is broken by normal faults and tension cracks, which trend about normal to the trend of the ridge. Person on the left side of the photograph gives scale. For photo location, see fig. 3.

normal faults and tension cracks, oriented at right angles with it (fig. 20). The normal faults form a series of small grabens, as much as 7 m wide and 3 m deep. These normal faults and tension cracks accomodate stretching of the flank ridge and indicate an increase in displacement rate here.

Within the body of the landslide, active ridges also form near strike-slip faults. They have in general the same characteristics as those along the flanks but are commonly smaller. Moreover, they appear to be more disturbed because of other differential movements within the landslide. As a result, there are scarps and tension cracks subparallel to the axis of these ridges combined with other features that apparently are not directly connected to their development and growth.

PONDS

Ponds are generally elongated parallel to the main direction of movement of the landslide. Their lengths, measured in this direction, range from a few meters to 150 m. Their widths, measured at right angles to the length, range from few tens of centimeters to about 90 m.

The ponds located near the strike-slip faults are typically much longer than wide and occupy the depressions formed when the sense of stepping is the same as the sense of slip: their width reaches a maximum of 5 m, while the length varies up to 40 m. The ratio length/width ranges from about 4 to 10. The ponds located in the middle of the slide have instead low values of the ratio length/width, with average value of 2.2. Their areas range from few square meters up to 10,500 m^2.

The ponds are typically in flat depressions behind a bulge of landslide material; the bulging causes the formation of a gentle uphill facing slope and consequently the stagnation of water (figs. 21 and 22). They are usually fed by the surface water system, but in some cases ponds are present with no apparent surface water stream inflow or outflow.

With the continuation of the movement, the ponds can be modified or abandoned, because of changes in the water system feeding them. As consequence of this, dry ponds and wet ponds are present on the landslide. The sediment in the dry ponds is characterized by light color, usually yellow, and by quite soft clayey material (fig. 21). Often polygonal dessiccation cracks are present on the margins of ponds. The ponds do not have vegetation, except for some young spruce and fir trees.

Wet ponds are dark and characterized by permanent stagnation of water (fig. 22). Most of them are not connected to the surface water system but merely fed by an inflow of water coming out the ground just uphill of the pond. A band of soil a few meters wide is saturated at the perimeters of the ponds. Algae growing in the ponds emphasizes their dark color.

Formation and development of ponds were already observed and described by Williams (1988) at active landslides in Utah.

Figure 21 - Downhill view of the main pond near station 3,000. Note the bulging and transverse cracks in the lower area. The length of the pond is about 150 meters, its width about 90 meters. Pond sediments are deposited at the right side of the area. Toward the left, at the downhill edge of the sediments, the surface is tilted upslope indicating that the failure surface in this area tilts upslope. Note that trees have been transported into the ponded area and killed by partial burial by sediments. Farther downhill in pond sediments, the old trees are absent and new vegetation has sprouted in the pond sediments. For photo location, see fig. 3.

Figure 22 - Example of small pond, looking downhill. Notice that the surface containing the pond faces uphill. The dark color of the pond is caused by algal growth. For photo location, see fig. 3.

Figure 23 - View of the active toe, which here is about 7 m high. The non-moving ground is in the foreground. Trees at left have been overrun by the toe. The trees in the middle of the view have been killed by partial burial by sediment washed from the actively moving part. For photo location, see fig. 3.

SPATIAL DISTRIBUTION OF STRUCTURES AT THE SURFACE OF THE ACTIVE LANDSLIDE

In this section the distribution of surface structures of the active Slumgullion landslide is described, starting from the upper part of the landslide.

Between stations 0 to about 800 m (plate 1), scarps represent the main structures; their origin is straightforward. Scarps are oriented approximately normal to the direction of movement, they range in height from a few centimeters to about 4 m, and they dip at steep angles of 50-70 degrees. A few scarps face uphill, but most face downhill; numerous tension cracks are intermixed with the scarps in this region. In all cases, these scarps appear to be created by normal faults.

The scarps must represent movement that has been occurring over a period of several years. We know from our estimates of rates of movement that the area containing many scarps is being displaced about 2.00 m/yr. There are many sets of scarps, and the total stretching indicated by summing the displacement on all the normal faults and tension cracks is many times greater than 2 m. The ages of the scarps cannot be more closely estimated without more detailed data on displacement and measurements of stretching strain.

On a bench between stations 800 and 1,100 m, the crack pattern changes from the pattern of closely spaced normal fault-scarps in the steeper ground upslope. The pattern is different on the left (south) side of the landslide from the right (north). Toward the left side, there are only a few scarps, and these are oriented mainly transverse to the displacement direction. These scarps together with associated tension cracks apparently also reflect stretching of the landslide but not in the direction of displacement. The intensity of cracking and scarp development is much smaller than farther uphill. Furthermore, the landslide surface here contains several dry ponds and back tilting of the ground surface.

Toward the right flank in the same area, the interval of stations 800 to 1,100 m, there is a zone of scarps and cracks oriented about parallel to the direction of movement. The scarps face both toward the landslide and away from it. Along this reach of the landslide, the width is about 300 m; the narrowest part of the landslide (150 m) is 600 m farther downslope. Also note a right-lateral strike-slip fault at station 1,200 that trends parallel to the overall displacement direction toward the right flank of the landslide to the place where the landslide abruptly becomes more narrow (station 1,300 m). Uphill from station 1,300 m, to station 800 m, the bounding strike-slip fault on the right flank is poorly expressed. Between stations 1,200 and 1,300 m, the bounding fault consists of fault segments without a throughgoing strike-slip fault. Farther uphill to about station 800 m, the position of the boundary is clear only from geomorphological evidence, as the boundary does not have fresh cracks.

We interpret the zone of scarps and open cracks between stations 800 and 1,100 m as a right-lateral shear zone. The movement is distributed over many separate faults, only a few of which were mapped as strike-slip faults. Along the right flank and outside the area of scarps, where the landslide narrows from 300 to 150 m, movement is too small to maintain fresh cracks along the flank. The entire zone between the cracks and scarps and the once-major boundary of the active landslide is now relatively dead.

At station 1,300 m, the landslide narrows from a width of about 300 m to 150 m, that is, the minimum width of the entire landslide. Just before the narrowing, there is the steepest ramp of the landslide, about 40 m high. The height of the ramp may be a consequence of the narrowing of the landslide: the amount of material that was uphill of station 1,300 m occupied a width of about 300 m. Transport of this material through the narrow section produced growth in height.

The main features observed are again represented by systems of scarps, both uphill and downhill facing, and by subordinate tension cracks. The scarps are transverse to the direction of movement. The presence of extensional structures on the ramp indicates stretching of the landslide also in this area.

The narrowest part of the landslide extends from station 1,300 to station 1,800 m. The narrowing was probably controlled by the shape of the pre-landslide valley, as reconstructed by Parise and Guzzi (1991). This area has the maximum rate of movement of the entire landslide, with average value of 6.00 m/yr (Crandell and Varnes, 1961).

The bench and ramp topography already observed in the upper part of the landslide continues between stations 1,400 m and 2,400 m, with benches and ramps of smaller size. Scarps, thrust faults, and strike-slip faults are present. The scarps are systematically transverse to the direction of movement, indicating stretching along the benches or in the rear part of the ramps. Other systems of scarps that are parallel to the direction of movement appear to be associated with strike-slip faults.

In the narrow part of the landslide, strike-slip faults and structures associated with them predominate. Other lateral discontinuities develop within the landslide: right-lateral and left-lateral strike-slip faults can be identified in this area, at distances of about 40-50 m from the right and left flanks, respectively, of the active landslide.

From about station 1,500 m downhill, most of the movement in the Slumgullion landslide is concentrated on or adjacent to its boundaries, as observed in other landslides (Keefer and Johnson, 1983; Lantz, 1984; Fleming and Johnson, 1989). Surface structures such as longitudinal sets of scarps, and en echelon tension cracks along the flanks, are mainly associated with strike-slip faults.

At station 2,500 m the landslide widens from 220 m to about 280 m, because of steps in the same sense of slip, for both the strike-slip faults bounding the flanks. Mostly extensional structures, such as basins, tension cracks, and scarps, are there observed.

From about station 2,800 m downhill, the active landslide widens on its right flank, so that the overall width increases from about 250 m to 430 m. This area is characterized by right-lateral strike-slip faults starting from the main shear surface that uphill marks the right flank of the landslide, and by structures associated with them.

The rate of movement of this area seems to be lower than that in the southern zone, included between the left flank of the active landslide and the extension of the main right-lateral strike-slip fault.

A series of thrust faults, almost continuous across the landslide, was mapped at about station 2,900 m. The thrust faults are oriented perpendicular to the direction of movement; few radial cracks, whose traces are parallel to the direction of movement, are associated with them. These features were interpreted as an active internal toe. Probably other minor toes of this type could be identified along the landslide, but in no other place was their evidence so fresh and clear.

Downhill of the internal toe, at about station 3,000 m, is the largest pond observed on the landslide (fig. 21). It is mostly dry, but a stream runs on its right side, soaking the soil for few meters in its vicinity. The lower part of the pond presents an uphill facing slope, with backward tilting of lacustrine sediments, measured at 6°. This area was interpreted by Parise and Guzzi (1991) as the point of emergence of the toe of the active landslide; that is, from there downhill, the active landslide overrides the old landslide topography.

The active toe, at station 3,200-3,400 m, in plan view is rounded and curved concave sourceward; in profile it has steep frontal slope, from 30 to 40 m high, with an average slope angle of 18° (fig. 23). Behind the toe, the slope angle decreases to an average value of 8°. The tip of the toe, closer to the left flank of the landslide, is at an elevation of 2,960 m. Only minor spreading of the material occurs at the toe. Its width is about 430 m, while in the area behind, the width of the landslide is about 370-400 m.

Along the central-left part of the toe, few cracks are present. They are generally limited to tension cracks, and subordinately to shear surfaces, with a mostly longitudinal orientation with respect to the landslide.

The principal feature on the active toe is a series of scarps, with height from 0.5 to 8 m. Most of them are the main scarps for minor landslides, mainly slumps. The biggest ones, on the northern side of the toe, were mapped. Small thrust faults are present in the area behind the tip, up to a distance of about 200 m from it.

Pressure ridges are present on the northern and northwestern sides of the toe (fig. 24). In the case of the pressure ridges located at the frontal part, and shown in figure 24 a and b, at least four steps are clearly identifiable, with height ranging from

(a)

(b)

Fig. 24 - Pressure ridges in marshy areas adjacent to the northwestern edge of the active toe: a) frontal view; b) lateral view. The steps are up to 1.2 m high, and broken by transverse cracks up to 0.8 m wide. For photo location, see fig. 3.

0.3 m to 1.2 m. The material is very soft and soaked with water; also ponds have formed in the area in front of the pressure ridges. Each step seems to push the one in front of it and in such a way to overthrust it. There are several tension cracks transverse to the steps, with width from 0 to 0.8 m, and variable orientation.

KINEMATICS OF THE ACTIVE PART OF THE SLUMGULLION LANDSLIDE

From the mapping and interpretation of surface structures and the analysis of rate of movement, three main kinematic zones were interpreted at the active Slumgullion landslide: a zone of stretching, a zone of strike-slip faulting, and a zone of shortening (fig. 25).

The zone of stretching extends from station 0 to 1,400 m, in the upper part of the landslide. It is characterized by scarps mainly transverse to the direction of movement. The rate of movement shows an average value of 2.00 m/yr.

The zone of strike-slip faulting, from station 1,400 to 2,800 m, consists mainly of the narrowest part of the landslide. The movement in this zone concentrates along the main strike-slip faults, both bounding the landslide and within it.

The formation and development of lateral discontinuities within the bounding strike-slip faults has been observed experimentally by Crosta and others (1991). They studied the development of flow of granular material in regions where obstacles are present, using a base friction table. In the case of confined experiments with sand, lateral discontinuities developed upstream of the obstacle, marking the boundary between rigid and plastic regions. As flow continues, these discontinuities reach the free surface and cause the formation of a conical depression: the material is forced to move along the sides of this cone toward the axis of symmetry, feeding the central region of high velocity (Crosta and others, 1991, p. 26).

The active part of the Slumgullion landslide presents characteristics similar to those observed by Crosta and others in their experiments: the maximum rate of movement of the entire landslide (6.00 m/yr) was in fact observed just downhill of the area where the lateral discontinuities clearly develop. Moreover, the middle part of the landslide, bounded by internal discontinuities, moves 0.75 m/yr faster than the flanks.

The zone of shortening extends from station 2,800 to the active limiting toe, at station 3,400 m. Active thrust faults, forming internal and limiting toes, are present transverse to the direction of movement. In the lower part of the active landslide, there are several right-lateral strike-slip faults that are approximately parallel to the direction of displacement. These faults apparently accommodate the change in amount of displacement across the surface of the landslide. The rate of movement ranges from 2.90 m/yr to 1.35 m/yr.

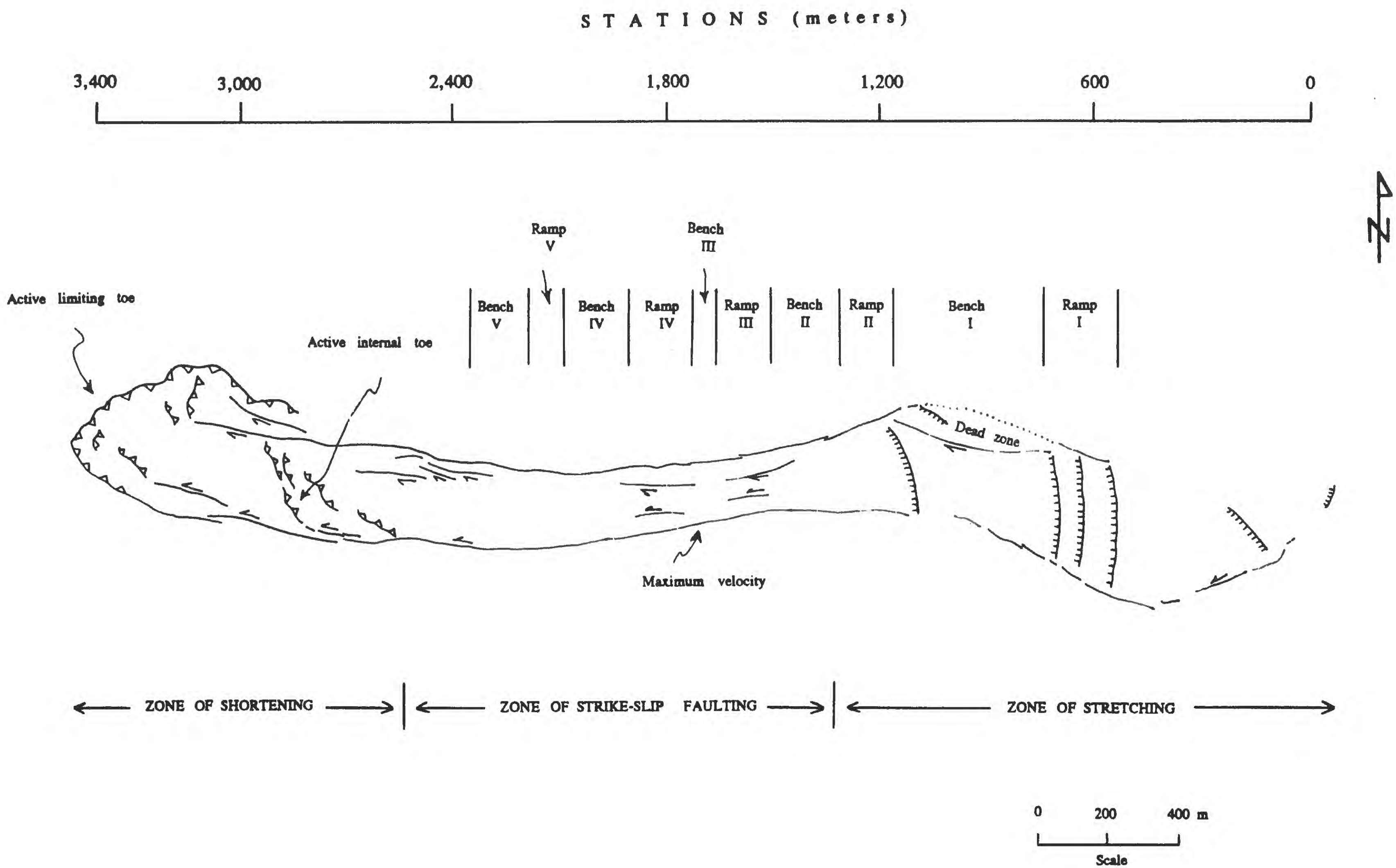


Figure 25 - Sketch showing the main areas of the active part of the Slumgullion landslide, inferred from the mapping and interpretation of surface features. Station line shown for reference to structures cited in text.

DISCUSSION AND CONCLUSIONS

Detailed mapping of the surface structures at the active part of the Slumgullion landslide, and their description and interpretation, were conducted in order to improve our knowledge on the landslide.

The ramp and bench profile of the Slumgullion landslide could be interpreted in two ways:

1) The alternating benches and ramps might mimic the topography of the slip surface, and the active part of the Slumgullion landslide consists of a single major landslide, with a few minor, shallow landslides on its surface.

2) The active part of the Slumgullion landslide is a multiple landslide, formed by several smaller landslides arranged end to end. The main slip surface is presumably an irregular surface that joins the surfaces of rupture of the single landslides. Each ramp and bench represents a single landslide; each ramp corresponds to the toe of a single landslide.

The distribution of structures and velocities at the surface of the landslide are more consistent with movement of a single large landslide over an irregular slip surface than with movement of several smaller landslides end to end.

The distribution of structures at the surface of the landslide, the kinematic zones from it inferred, and the movement data here presented, follow the trend already observed in other landslides (Keefer and Johnson, 1983; Lantz, 1984; Fleming and Johnson, 1989; Baum and others, 1989; Baum and Fleming, 1991).

Several areas for future research may improve understanding of the Slumgullion landslide. Systematic study of position and ages of the flank ridges could provide information on the early history of movement of the landslide. The marked contrast in size of old, inactive compared to active ridges could be related to the difference in the computed volumes for old and active parts of the landslide. The active part contains an estimated volume of 19.5×10^6 m^3, only about 12 percent of the total volume of material involved in the Slumgullion landslide (Parise and Guzzi, 1991). Other interesting information could come from the measurements of surface displacement of the landslide using analytical stereoplotter and comparing the locations of photo-identifiable points on different sets of aerial photographs taken in successive years. Both the values of displacements and velocities along the landslide, and the direction of the displacement vectors, will make it possible to assess the distribution of deformation on the surface of the landslide.

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